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TECHNICAL PAPERS ON TARGET VULNERABILITY ANALYSIS INTENDED FOR A BRIEFING TO INDUSTRY

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Four technical papers on the subject of Target Vulnerability are presented. The first paper "Vulnerability Overview" discusses the scope of vulnerability analysis and vulnerability reduction and their application to military equipment. The second paper discusses methods of performing vulnerability analysis. Principles of reducing the vulnerability of materiel are treated in the third paper. Finally, the origin, purpose and status of the Vulnerability Analysis Teams at the Commodity Commands are discussed in the last paper.

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I. INTRODUCTION

A briefing to U. S. industry was planned for 6, 7 March 1974 at the Ballistic Research Laboratories. The purpose of the briefing was to make industry aware of and more responsive to both target vulnerability analysis and human factors engineering in the development of materiel for the U. S. Army. The vulnerability analysis part of the briefing was intended to introduce industry to the scope, principles and analytical methods of vulnerability analysis and vulnerability reduction and to inform industry of the rationale for and status of the Army's Vulnerability Analysis Teams. Vulnerability analysis provides systematic quantified assessments needed to determine the survivability of U. S. Army materiel and personnel in battlefield environments as well as to determine the expected performances of our weapons against foreign materiel. The scope of the human factors engineering part of the briefing was intended to cover programs, requirements and integration of man in the man-machine system in order to utilize man's capabilities and to compensate for his limits in the operation and maintenance of the systems. The briefing would indicate the capabilities industry needs to perform these analyses and would point out the sources of assistance industry could call on so that these disciplines could be integrated into design and development for optimum survivability or lethality of military equipment.

The briefing was cancelled due to the energy crisis that existed in this country at that time. However, the technical papers that were prepared for the briefing have been collected. Those concerning human factors engineering are being published separately from the vulnerability analysis papers. The purpose of the present report is to publish the papers on vulnerability analysis. In this manner the formal technical intention of the briefing will be fulfilled despite the cancellation.

VULNERABILITY OVERVIEW

Alvan J. Hoffman

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Introduction

An overview of any subject often tempts one to make a few generalizations. I trust this general view of Vulnerability will be more than that and thus give you some appreciation of what vulnerability and its counterparts (vulnerability reduction and survivability) are. I'd like to also tell you how we do it, and what it's used for.

Vulnerability is not new subject to the Army. In fact, we've been quantifying the effects of damage on targets for well over 25 years. At first vulnerability studies were done to find out what really damaged targets and to learn how we could make weapons to do what we wanted them to do. We also learned much about the potential of our own weapons system to withstand various damage and sought ways to protect them. Industry, for the most part, has not been considering vulnerability and survivability in design and development of equipment for as long as the Army. In fact the posture of industry is pretty much as we see in Figure 1. With some exceptions, the situation in 1960 and prior years was, "How do you spell it?". By 1965 that was well in hand, but survivability was the new word.. What is it? Does DOD require it? The contracts rarely mentioned it or required it. By 1970, however, many companies had established vulnerability and survivability teams, but these couldn't compete with performance, cost or other requirements stated in contracts. They needed (and still do) more and better data. By 1975 and beyond, however, things look considerably better, but with a big challenge yet to be dealt with by industry and the Army.

Even with the efforts that industry and the Army have put forth in the past decade, collectively we've still not gotten very far, Figure 2.

In Viet Nam this was a typical scene! This helicopter was forced into a crash landing because the pilot lost control after a small component failure, Figure 3. This is the component: a hydraulic actuator whose case was dented by a fragment or projectile making it impossible for the piston to move back and forth as it should.

Another example of battlefield damage is shown here on a locator, Figure 4. This was damaged by several bullets and fragments to the point where it was useless. In the case of the bullet damage which you see in the upper portion, the holes produced in the slip ring assembly caused failure of the system. This is an example where even the slightest amount of damage renders the whole system incapable of performing its intended function.

1960 - - VUL_ _ _ _ _ITY? HOW DO YOU SPELL IT?

1965 - - SURVIVABILITY? DOD REQUIREMENT?
(CONTRACTS DIDN'T SAY SO)

1970 - - COMPETENT COMPANY S/V TEAMS EXIST
(PROBLEMS MEETING REQUIREMENTS–
INSUFFICIENT DATA)

1975 - - CLEAR, STRONG, DOD HIGH PRIORITY
S/V REQUIREMENTS
(DEMONSTRATED DOD TECHNOLOGY AND
FACILITIES TO EVALUATE DESIGNS AND
VERIFY CLAIMS)

Figure 1 Industry Posture

Figure 2 Downed Helicopter

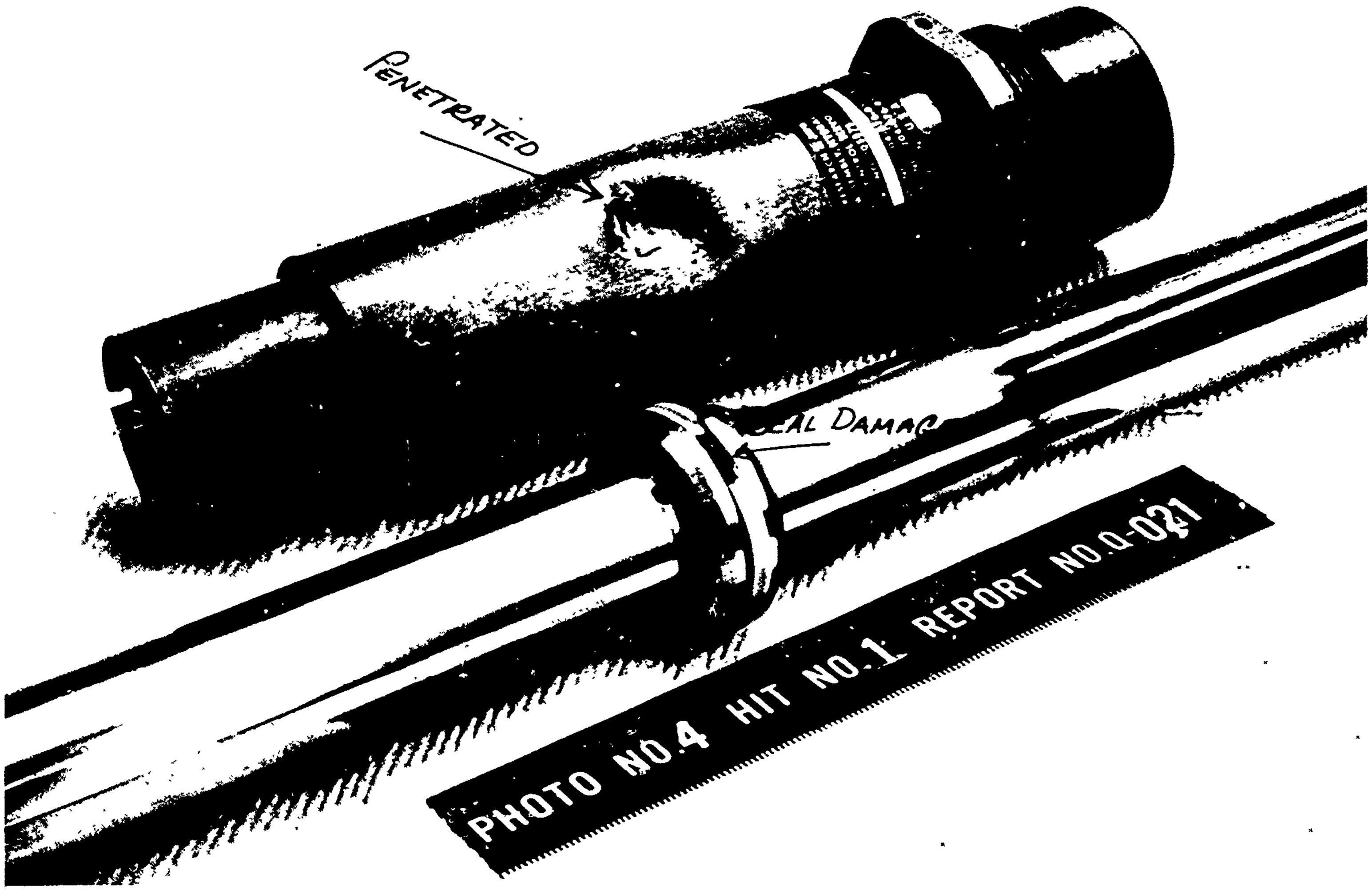
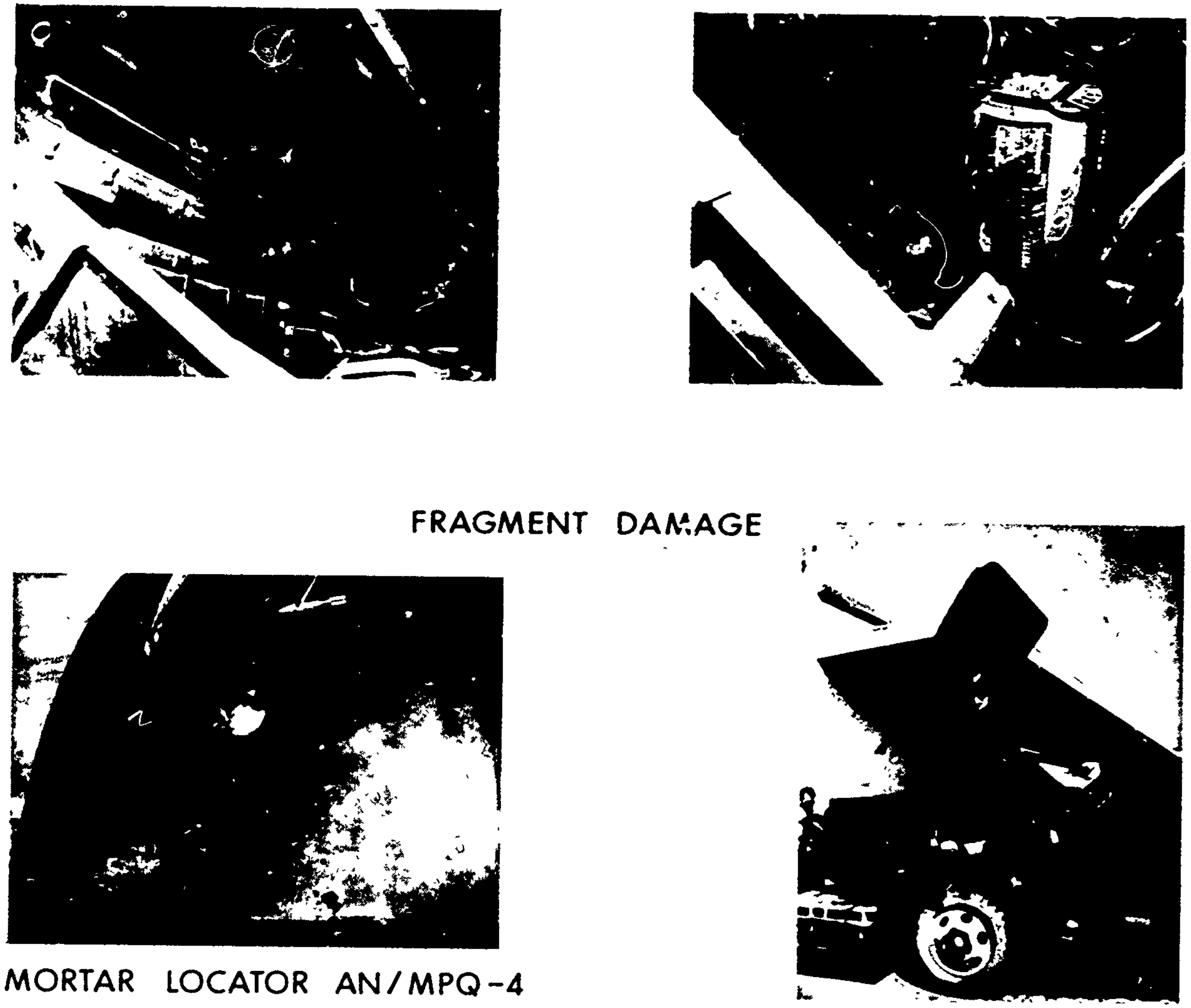


Figure 3 Damaged Hydraulic Actuator

BULLET DAMAGE

FRAGMENT DAMAGE



MORTAR LOCATOR AN/MPQ-4

Figure 4 Mortar Locator Damage

We've had trouble also with the design of our munitions. Sometimes we design them without a careful study of the vulnerability of the targets they are designed to defeat. Figure 5 shows a shaped charge warhead with the fuze in the spike. This works well if the spike strikes the target first as you see at the top. If the shoulder strikes some object first, as seen at the bottom, there is no proper jet formed and consequently no perforation of the armor.

Figure 6 shows how serious the problem is on a tank. There is extensive area where shoulder impacts can take place with a resulting serious loss in munitions effectiveness. We've had to fix this round by putting a different fuze in it to permit proper detonation when these shoulder impacts do take place.

We've had success in hardening some of our equipment to withstand battle damage by adding on kits of various types. Moreover, these have saved lives, but it was costly to do. We learned from Viet Nam that reduced vulnerability can be designed into machines and we've obtained data from combat to help show us how to proceed. These data have been used to some extent by industry and when the problem is understood, industry usually finds good engineering solutions to increased survivability.

At this point I'd like to define several terms. They are Vulnerability, Vulnerability Reduction and Survivability, Figure 7. Vulnerability is a quantitative measure of the susceptibility of a target structure or material to a given damage mechanism. This is usually the starting point for determining the effectiveness of a munition on a target for which it is intended. Vulnerability data, along with other major factors, such as delivery accuracy, weapon characteristics, reliability and human factors have to be systematically determined. All these data are combined through appropriate methodology (which we'll be talking more about during these briefings) to yield complete weapon effectiveness values. This information makes it possible, first of all, to determine the potential of our weapons to defeat enemy targets. This, in turn, enables us to improve them. Secondly, it allows us to derive criteria for reducing the vulnerability of our own materiel and personnel systems, thereby leading to their increased survivability.

This brings us to the second term, Vulnerability Reduction and its definition, Figure 8. Vulnerability Reduction is the application of design techniques to materiel items to reduce or eliminate the effects of combat damage. This is the other side of the Vulnerability coin and these techniques and principles are best applied during the design and development phase. When done at this point, we can take full advantage of all the tricks and can often come up with smaller items of less weight which are less vulnerable. It can also be done with less costs than add-on kits. Mr. Vikestad will speak at length on the principles which govern this part of the work.

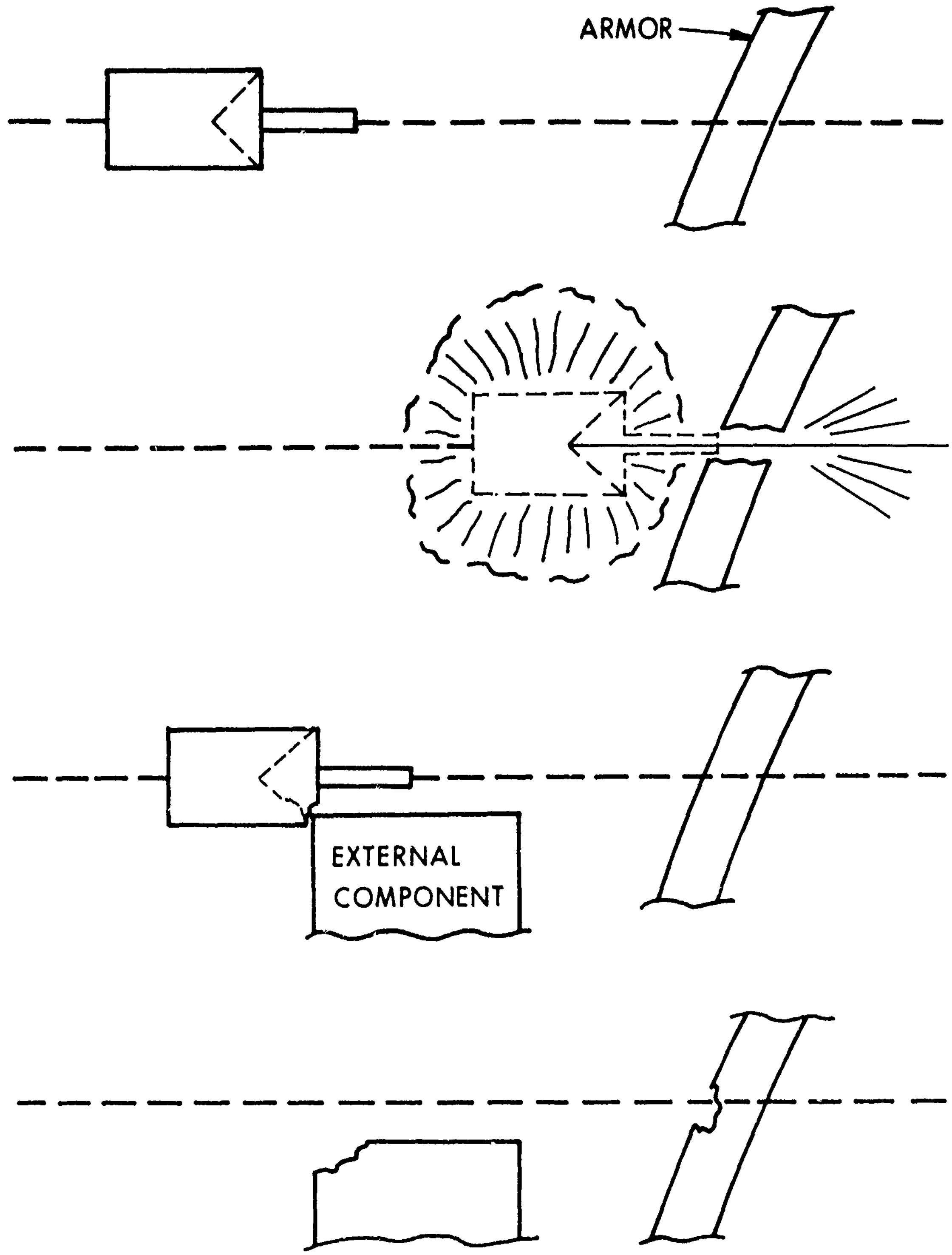


Figure 5 Shaped Charge Projectile Functioning

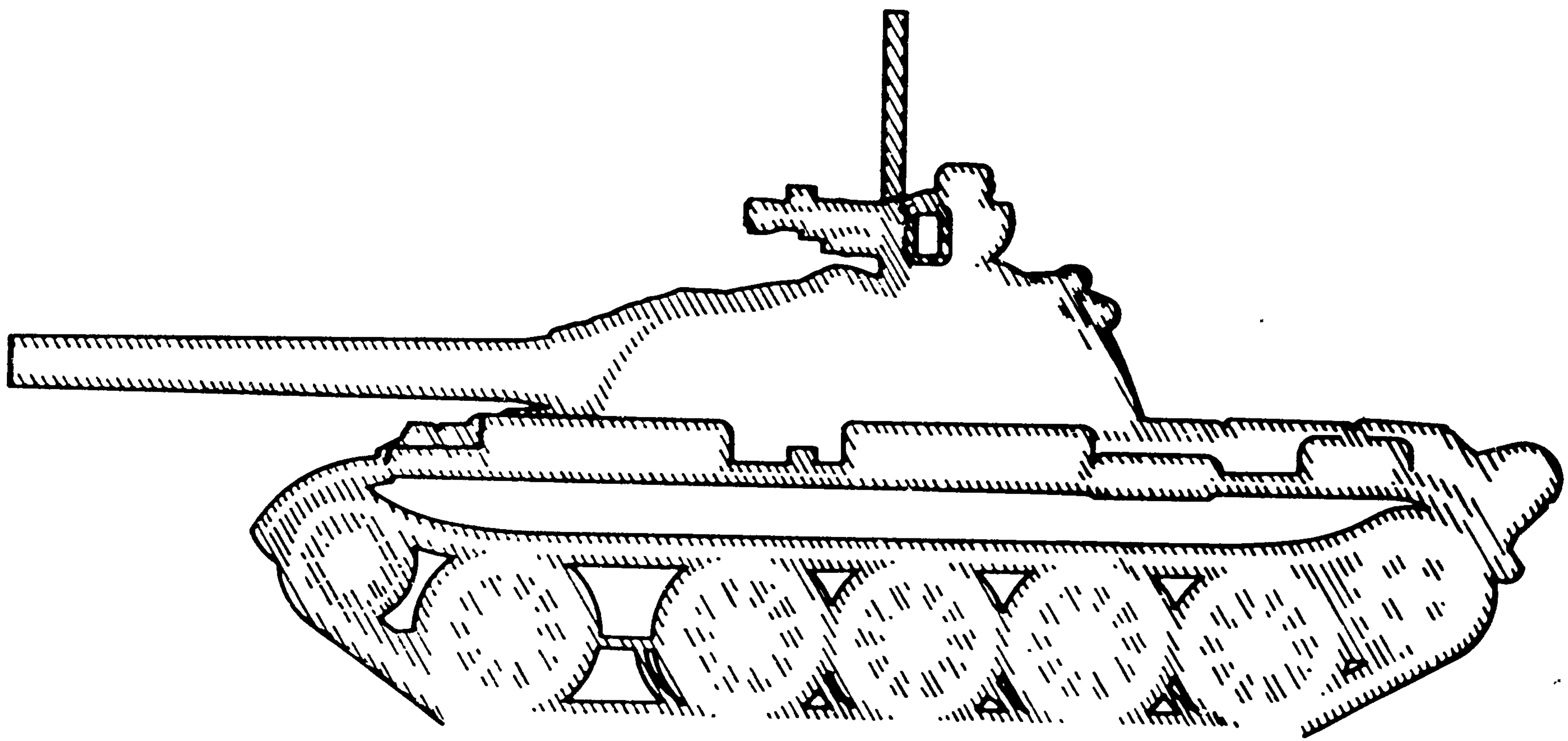


Figure 6 Areas Where Shoulder Impacts Degrade Munition Effectiveness

A QUANTITATIVE MEASURE OF THE SUSCEPTABILITY OF A TARGET STRUCTURE OR MATERIEL TO A GIVEN DAMAGE MECHANISM.

Figure 7 Vulnerability

THE APPLICATION OF DESIGN TECHNIQUES TO MATERIEL ITEMS TO REDUCE OR ELIMINATE THE EFFECTS OF COMBAT DAMAGE MECHANISMS.

Figure 8 Vulnerability Reduction

THE ABILITY OF SYSTEM TO AVOID OR WITHSTAND DAMAGE WHILE PERFORMING A DESIGNATED MISSION IN A HOSTILE COMBAT ENVIRONMENT.

Figure 9 Survivability

The third term, Survivability, we define as the ability of a system to avoid or withstand damage while performing a designated mission in a hostile combat environment, Figure 9. This means that once we have a weapon system or a piece of equipment built and in the field there may be additional measures taken to further protect it under fire. For example, the user might revet certain portions, put some armor protection on critical items, relocate certain components, bury cables, camouflage or operate in such a way that he is less detectable. Our users need whatever vulnerability analysts can provide to show him how he can maintain some degree of operational capability after suffering damage or how he can maintain full capability under a greater threat.

These definitions which I've stated are given in Army Materiel Command (AMC) Regulation 70-53 "Non-Nuclear Vulnerability and Vulnerability Reduction" dated 16 June 1971. I might point out here, that an AMC regulation covering Nuclear Vulnerability has been proposed but not yet formalized. The vulnerability and vulnerability reduction areas are the ones we'll be concerned with in the design and development of weapons. The survivability area is where we'll seek to assist the military in the use of weapons in the field.

As I said earlier, a meaningful analysis of vulnerability requires that we quantify various damage mechanisms in terms of target response. Figure 10 lists the target types of concern to the Army and the various damage mechanisms which are considered. Each category has many specific targets to be studied and the results must be quantified for one or even several of these damage mechanisms. Blast - I think you are all familiar with this. Penetration includes bullets, fragments, rods, shaped charges, etc. Chemical mechanisms include additives which degrade the performance of such things as fuel. We've had limited effort and experience in this area. With lasers becoming more important, we are involved in studies associated with their effects on targets suseptible to heat and perforation by burning. Radiation includes initial, residual and fallout from nuclear detonations. Of course, we don't have all the terminal effects data or even the damage criteria we need for all of these mechanisms, but our programs in the Army are geared to getting them.

Vulnerability analysis might logically be done any one of several different ways. For example, we might fire munitions at targets and statistically determine what happens. A good deal of this has been and still is being done. However, more often than not targets and munitions are not available for testing and we have to obtain answers by performing some kind of an analysis using what we know about a target and terminal effects of munitions. Let me describe this latter process a little further.

Figure 11 shows the essential elements of such an analysis. We must first select the target. It may be the one in which we are actually interested or, if we don't have that particular one, we may select one that is representative of the class of targets in which we are interested. As a case in point, we may not have information to allow us to perform

TARGET CATEGORIES	DAMAGE MECHANISMS
AIRCRAFT	
ANTI-A/C ARTILLERY	
ARMORED VEHICLES	
ASSAULT GUNS	
BUILDINGS	
COMMUNICATIONS EQUIPMENT	BLAST
FIELD ARTILLERY	PENETRATION
FIELD FORTIFICATIONS	FLAME & INCENDIARY
LAND TRANSPORTATION	RADIATION
MISSILE SYSTEMS	CHEMICAL
PERSONNEL	LASER
POWER GENERATION FACILITIES	
RADAR INSTALLATION	
ROCKETS & LAUNCHERS	
SUPPLY DEPOTS & DUMPS	
SUPPORT VEHICLES	

Figure 10 Scope of Research

- TARGET SELECTION
- TARGET DESCRIPTIONS
- DAMAGE OR KILL CRITERIA
- CONDITIONAL KILL PROBABILITIES
- METHODOLOGY
- WHOLE TARGET VULNERABILITY DATA

Figure 11 Elements of Vulnerability Analysis

an analysis of a particular Soviet tank, but we may have data on a similar one which will suffice for that class of vehicle. Once we've made this selection we can then follow these subsequent steps to yield whole target vulnerability data.

The next step is to develop a target description, Figure 12. What is this? It's a mathematical representation of the target in which all elements are described in geometric form. It's the actual size and shape of the target to be sure, but it is more than these. It includes basic information relative to dimensions, configuration, functional or operational data, locations of critical or potentially vulnerable components and types and thicknesses of materials. We get this information from intelligence data for foreign targets or actual survey of our own system. The exact content and form of the description depends on the detail of the analysis and the degree to which we have the needed information.

Figure 13 shows a view of a tank at 45° azimuth and 45° elevation. It is a drawing produced by the computer based on the information put into it. In other words the computer draws for us in any view what it believes the target is.

Figure 14 shows a similar description of a Vulcan gun with the picture at the top and the computer representation at the bottom. These descriptions give great flexibility in obtaining presented areas of the target. They also provide detailed information relative to the components along a shot line taken through the target and this lets us assess potential damage from any attack direction.

It is also possible to describe the human as you see on Figure 15 by the Computer Man.

The vulnerability of a target should also be expressed in terms of the results desired when the target is attacked. These results are called damage or "kill" criteria. These vary depending on the target and Figure 16 lists several examples. Some of these relate to the tactical situations where target performance should be degraded as quickly as possible. Examples are catastrophic kill, a mobility kill or firepower kill which are used in the case of a tank. Other damage criteria relate to cost inflicted on the enemy in terms of time to repair or replace. This type of kill we call an interdiction kill where the times to repair are assessed for either an expedient fix of the target or a thorough reconditioning. The attrition, forced landing and mission kills deal with aircraft. There are also several others which deal with personnel incapacitation. In most cases a time to achieve the kill is also established. Here are several illustrations of kills:

Figure 17 shows a catastrophic kill where the truck is a complete loss due to blast.

- DIMENSIONS
- CONFIGURATION
- MATERIAL COMPOSITION
- FUNCTIONAL OR OPERATIONAL DATA
- LOCATION OF CRITICAL COMPONENTS
- SHIELDING OF RELATIVE COMPONENTS

Figure 12 Target Description

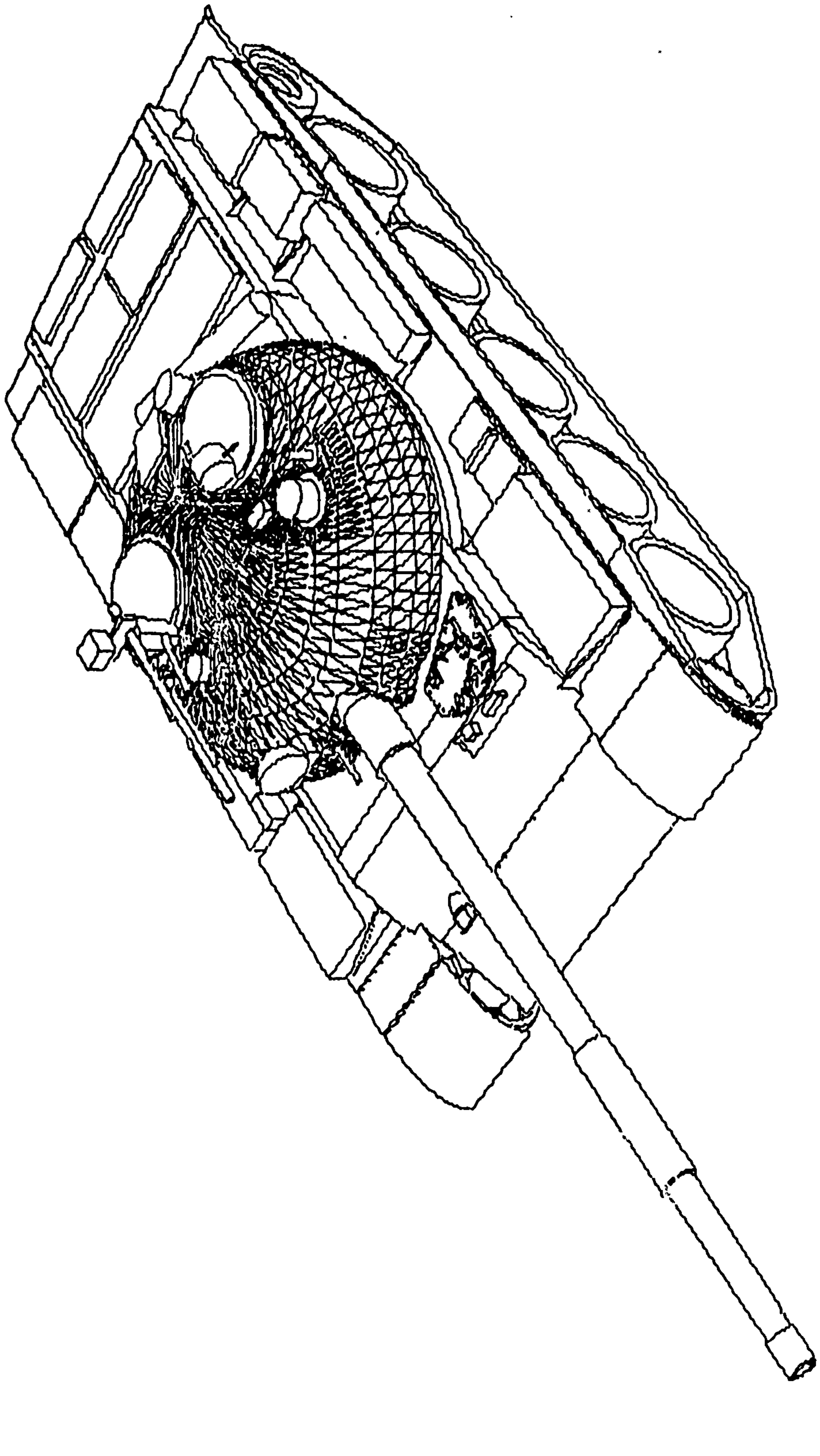
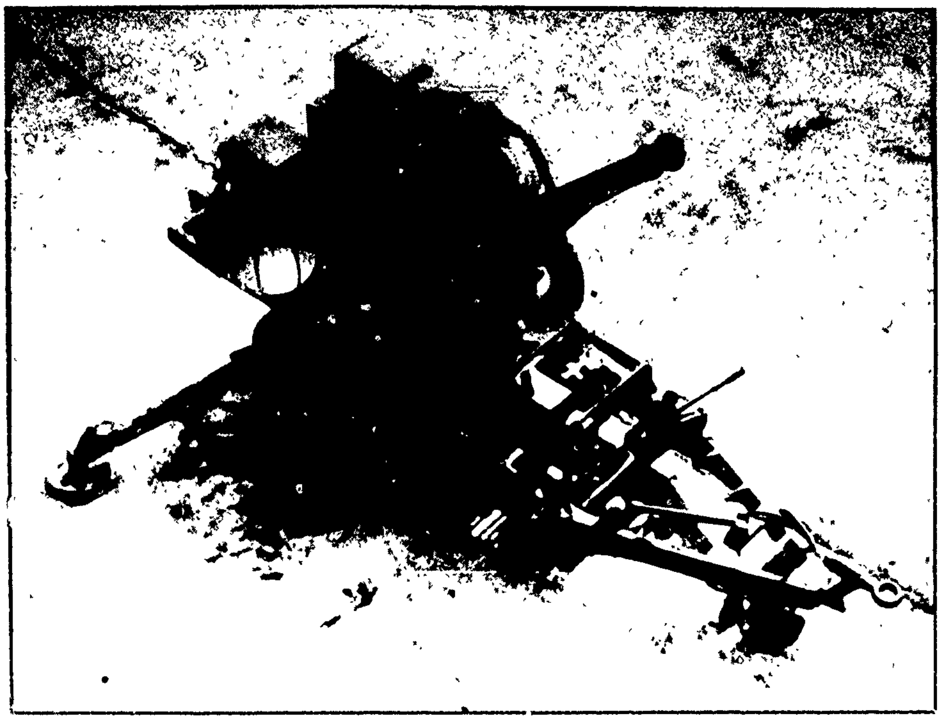
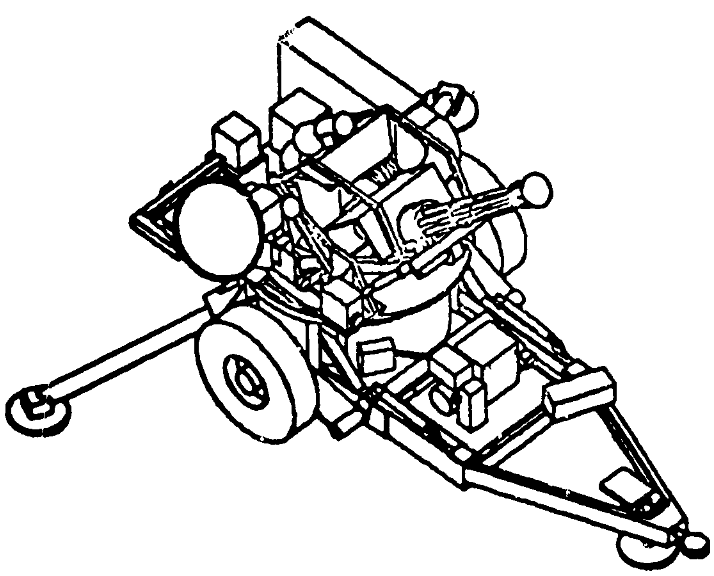


Figure 13 Computer Description of a Tank





20 MM TOWED ANTIAIRCRAFT VULCAN CANNON XM167(XM168 XM61
AZIMUTH 315.0 ELEVATION 45.0
SCALE IS 45.00 = 1.0

Figure 14 Vulcan Photo and Computer Description

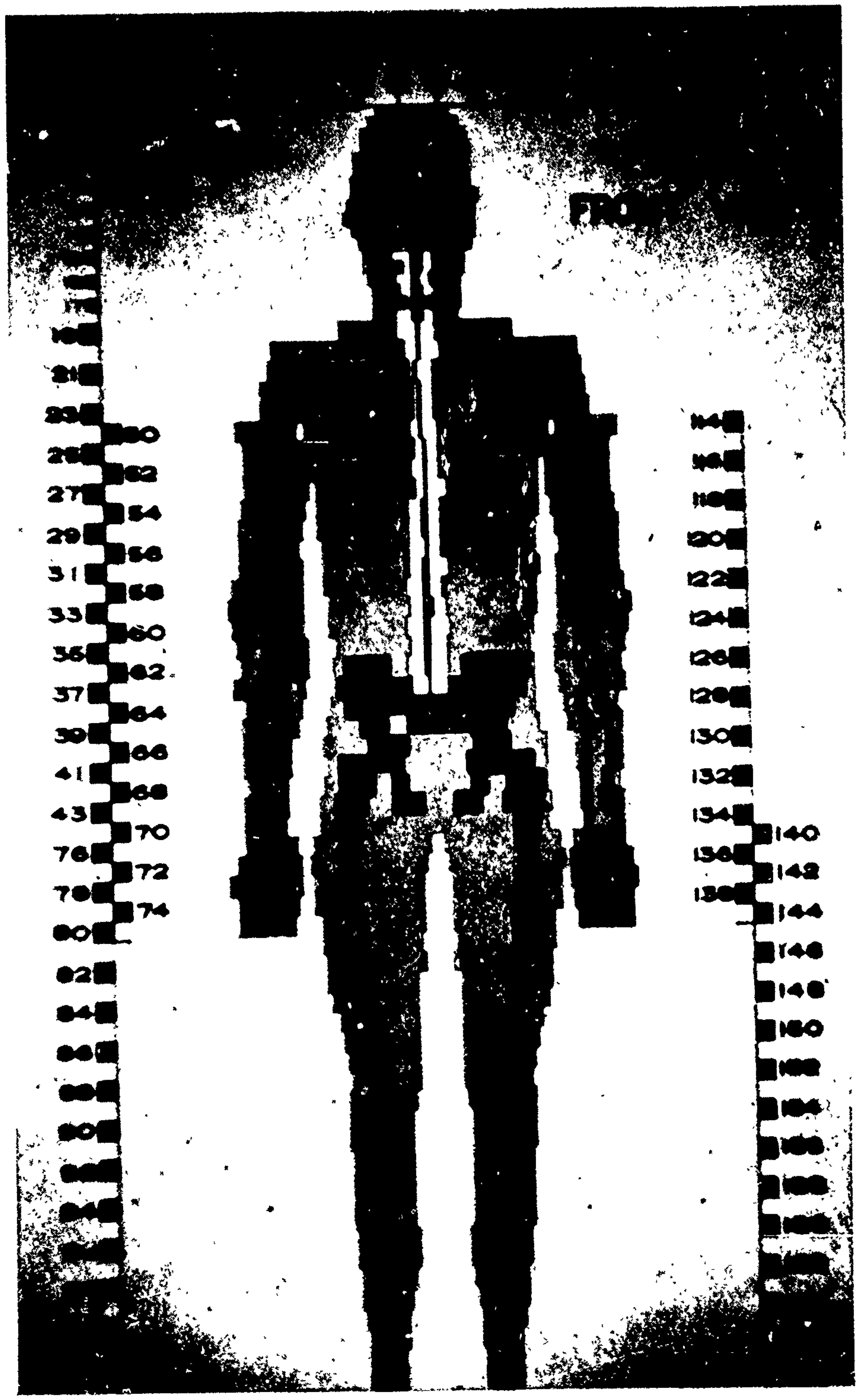


Figure 15 The Computer Man

EXAMPLES

- CATASTROPHIC KILL
- MOBILITY
- FIREPOWER
- INTERDICTION
- ATTRITION
- FORCED LANDING
- MISSION
- PERSONNEL

Figure 16 Damage Criteria

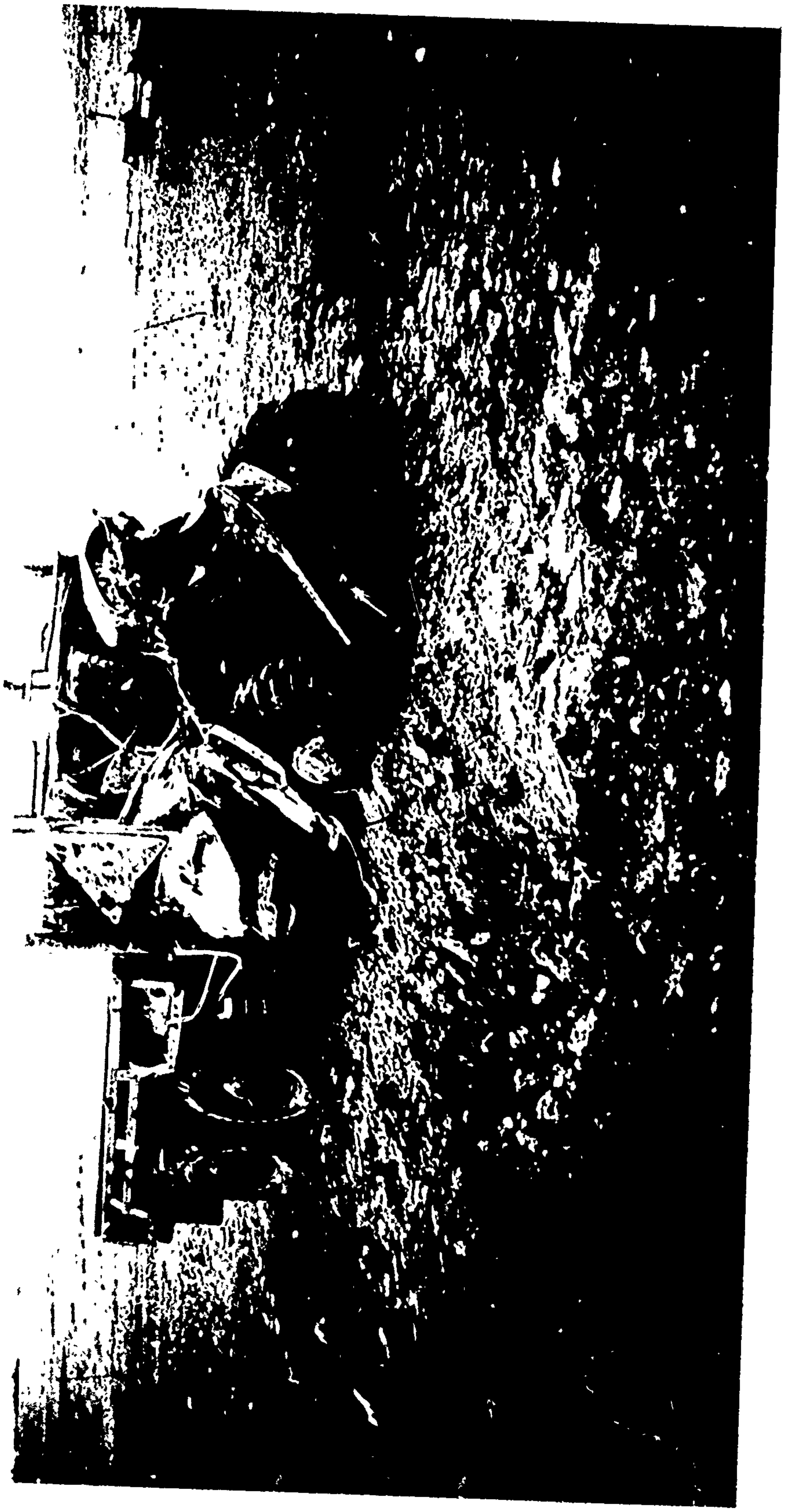


Figure 17 Catastrophic Kill of Truck

The damaged tank on Figure 18 would represent a mobility kill since the track has been blown off and the road wheels severely damaged.

Next, conditional kill probabilities, for given damage mechanisms are needed. Consider, for example, a small fragment hitting the wheel of a truck. What is the likelihood that it can degrade the performance of the truck? Figure 19 shows that up to a velocity of 1200 feet/second there is no damage. As velocity increases for hits from any direction, the probability of damage or "kill" increases until, at slightly over 4000 feet/second, this fragment reaches its maximum potential for damage of the wheel or tire. These $P_{K/H}$'s, as we call them, are obtained for several attack directions and then averaged for use in the analysis. We have analytical procedures for obtaining kill probabilities on many targets and components but some data of this type are obtained by experiment especially in cases where we have little experience or where the damage may be marginal. As much as possible, people who understand and use the materiel in question assess this performance degradation in terms of the damage sustained.

Having developed these target descriptions, damage criteria and component conditional kill probabilities, we can now derive the whole-target vulnerability to the various damage mechanisms. To do so, we must have appropriate methodologies. The calculation requirements generally lead to computerized models. Figure 20 is a list of some of the useful models which we now have. Included are several target description models, assessment models for armored vehicles, trucks, missile systems and bridges, a $P_{K/H}$ methodology, a personnel casualty model and several others including fuel fire ignition and fuze response for projectiles. These models may be either parts of an analysis procedure or complete vulnerability assessment programs. Most models tend to become rather complex primarily because most of our targets are complex. Complexity is inherent also because we attempt to account for all factors involved in the problem. Wherever possible, however, we aim to develop basic and general solutions for handling classes of problems. These general models indicate quite strongly what parts of the problem influence the final results the most and the degree of accuracy to which we need to obtain the input data. Once we have this feel for the sensitivity of inputs of the problem, it is possible and even desirable to simplify the model accordingly for use by system designers and developers such as yourselves.

The results obtained from these models take several forms, Figure 21. First of all, we can produce what are called vulnerable areas which are compatible with systems analysis programs. Tables of these are given as functions of mass and velocity of the penetrator for a given level of kill or incapacitation given a hit or total probability of kill estimates for specific weapon-target encounters. We can also provide distances about the target for given levels of damage.

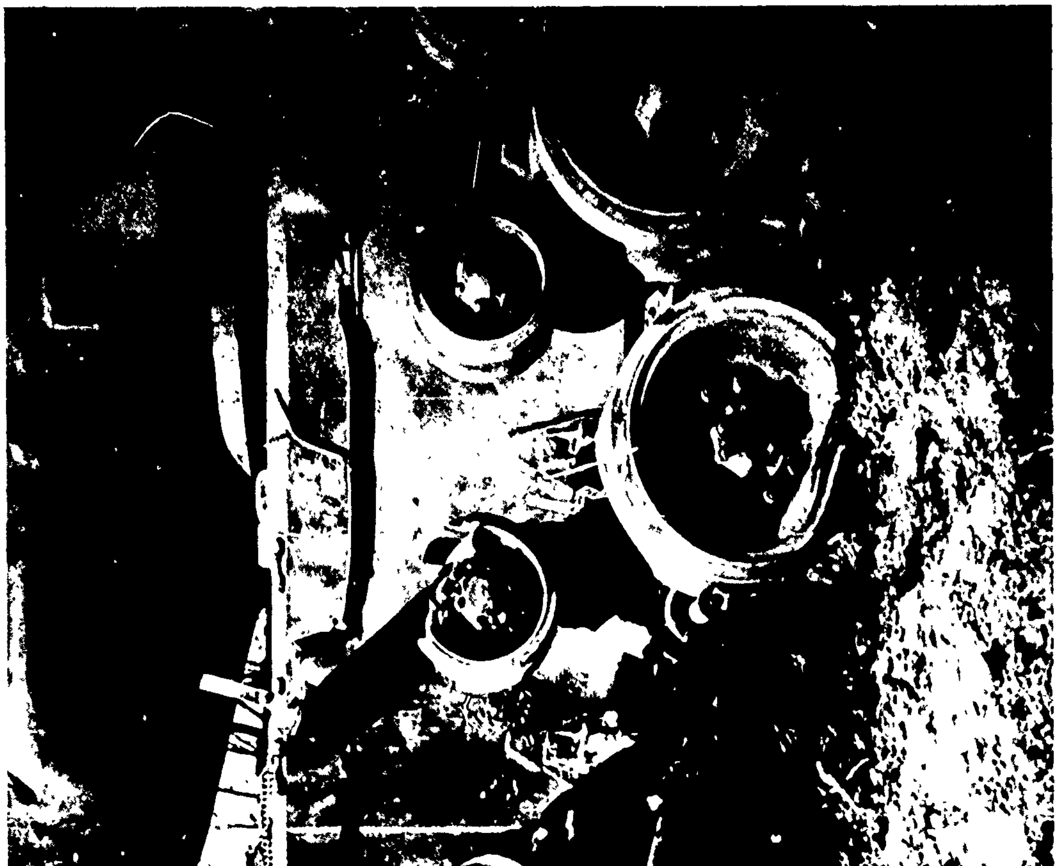


Figure 18 Mobility Kill of Tank

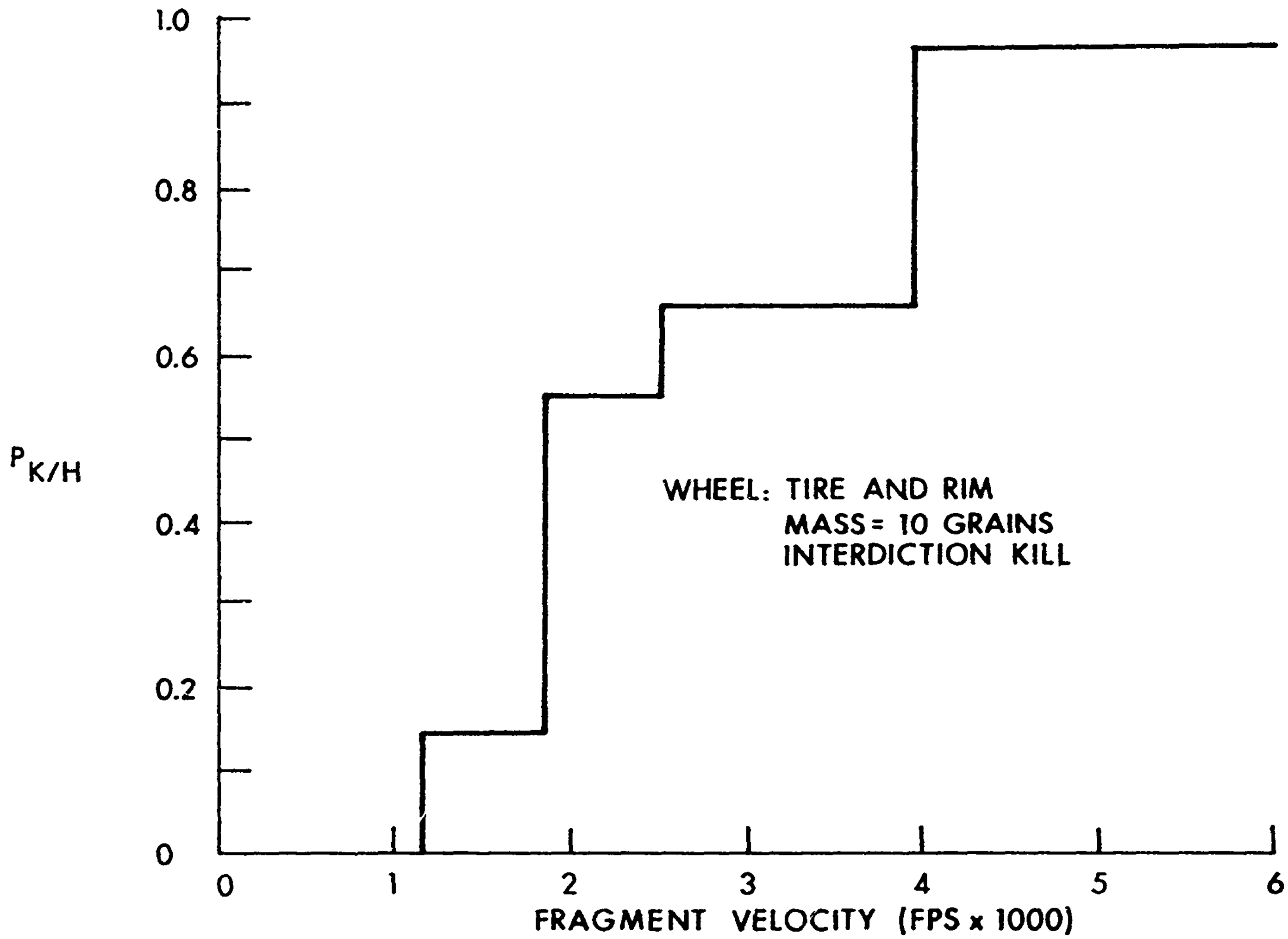


Figure 19 Kill Probability Function

- TARGET DESCRIPTIONS
  - COMBINATORIAL GEOMETRY
  - TRIANGULAR
- PENETRATION - HOLE SIZE, RESIDUAL FRAGMENT VELOCITY AND MASS
- ARMOR ASSESSMENT - SHOT LINE
- TRUCK ASSESSMENT - POINT BURST/PARALLEL RAY
- MISSILE AND VAN ASSESSMENT
- BRIDGE ASSESSMENT
- $P_{K/H}$ METHODOLOGY
- BLAST
- PERSONNEL CASUALTY - COMPUTER MAN
- FUEL FIRE IGNITION
- MINES AGAINST TANK HULLS
- FUZE RESPONSE

Figure 20 Vulnerability Models

- VULNERABLE AREAS
- MISS DISTANCES
- P_{HK}

Figure 21 Forms of Vulnerability Data

Figure 22 provides an example of such a damage contour about a tank to indirect fire from a U.S. 155 mm HE shell. Such contours represent a given level of kill. In this case it represents a 0.5 probability of a mobility or firepower kill. Outside the contour you would expect something less than 0.5 and inside something greater. These data are very useful in establishing acceptable miss distances and fuze requirements. The raw data for making these assessments were derived from tests. Similarly we can derive data about other targets which are blast sensitive such as aircraft.

Vulnerability analyses, including vulnerability reduction and survivability, require a considerable amount of input data. On Figure 23 you see the types needed such as ballistic, medical, operational, design and intelligence data. These data come from many sources throughout the services, industry and even the hospitals in the case of vulnerability and survivability of the soldier.

Figure 24, for example, shows the kind of data required to assess vulnerability where spall plays an important part in the damage to a target. In this case, a shaped charge strikes a material causing many fragments to spall off and go in directions different from the jet. The jet itself may or may not strike critical components, but the fragments because of their mass, velocity and spatial distribution may cause considerable damage to critical components. These and similar data from kinetic energy penetration are obtained and quantified for vulnerability assessment. Moreover, these data show what must be stopped for effective spall suppression inside targets such as tanks or bunkers.

How and when do we use the data derived from vulnerability analysis? Perhaps the character of the different types of vulnerability, vulnerability reduction or survivability studies are best understood when put in perspective of the normal life cycle for Army materiel. Figure 25 basically shows the life cycle as defined under the current procedures for materiel acquisition. Of course, it is quite simplified, but shows the various phases from requirement to salvage.

The first step is preparation of Required Operational Capability which is called a ROC, Figure 26. In recent years the Vulnerability Laboratory has become increasingly active in working groups whose objective is to formulate the initial requirements document. Sometimes such activity involves conducting new analytical studies to provide guidance on specific problems. Most frequently, however, our input is based on results of previous studies and the experience of our people. Industry is seldom, if ever, involved at this point.

At concept formulation industry is involved and should be aware of vulnerability pitfalls, Figure 27. Normally, the objective of these early analytical studies is to examine a relatively large number of candidate designs, and to filter out those which show the most promise of meeting the conflicting requirements posed by the user. Because of

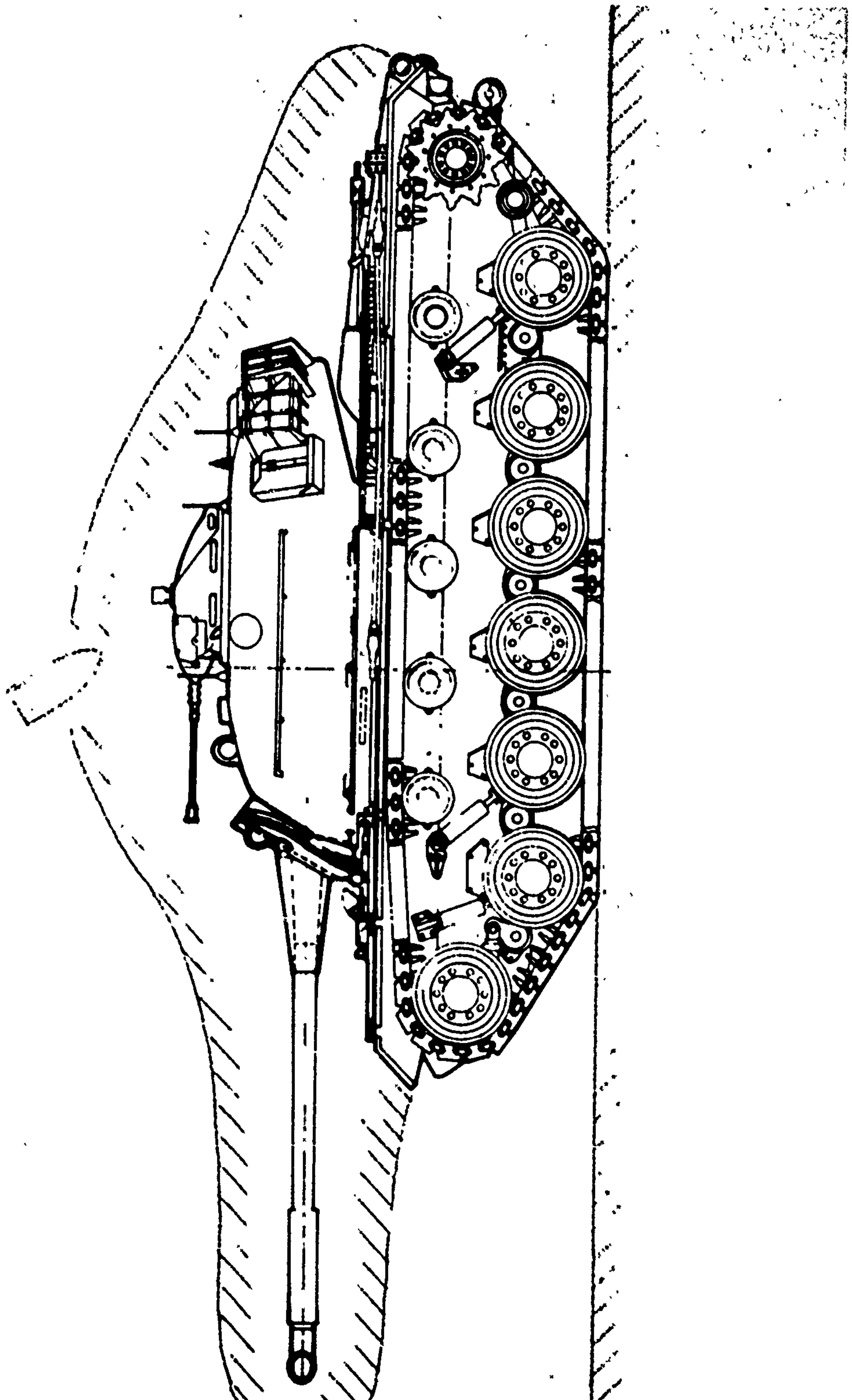


Figure 22 Kill Probability Contour About a Tank

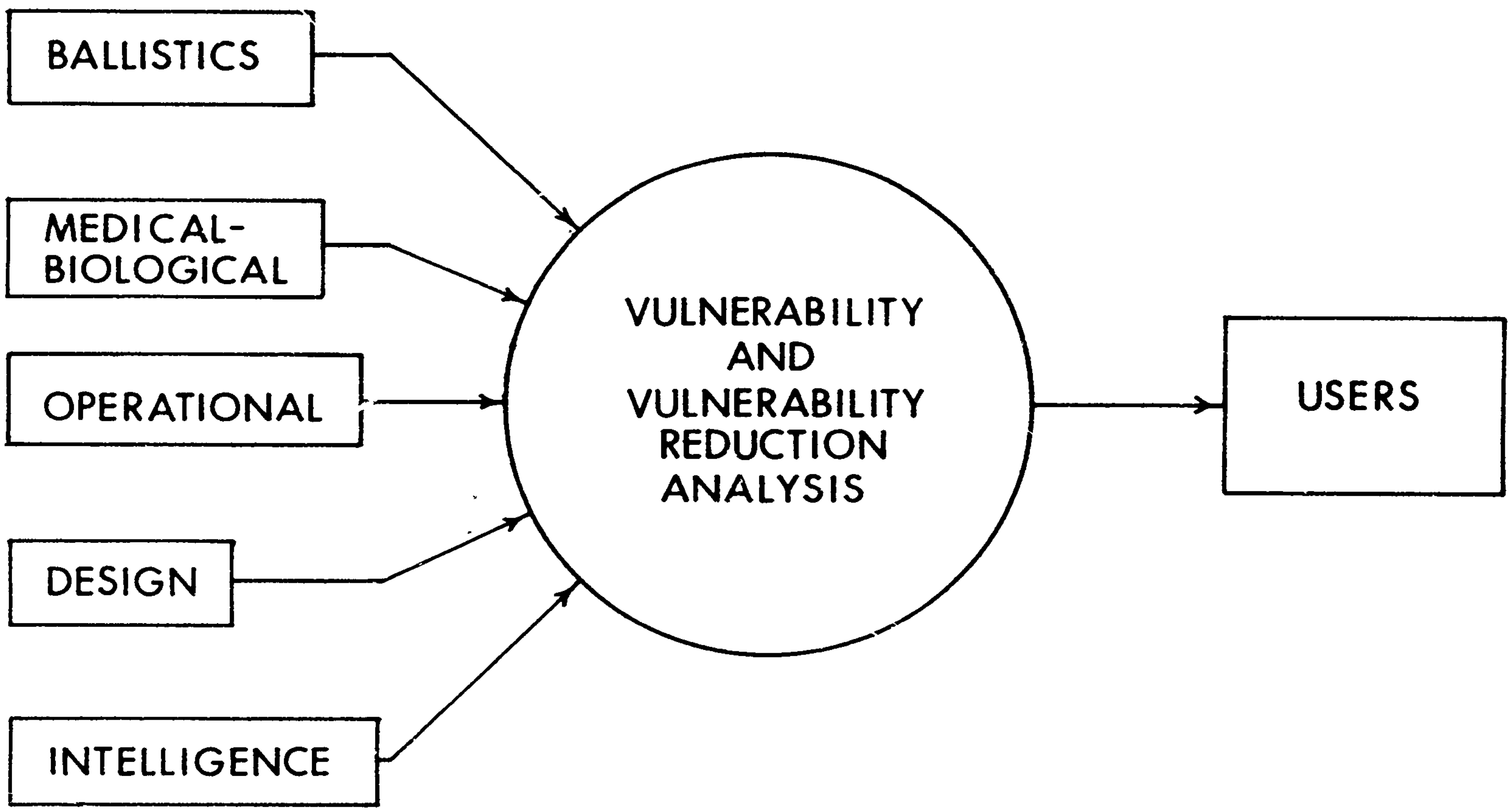


Figure 23 Types of Input Data

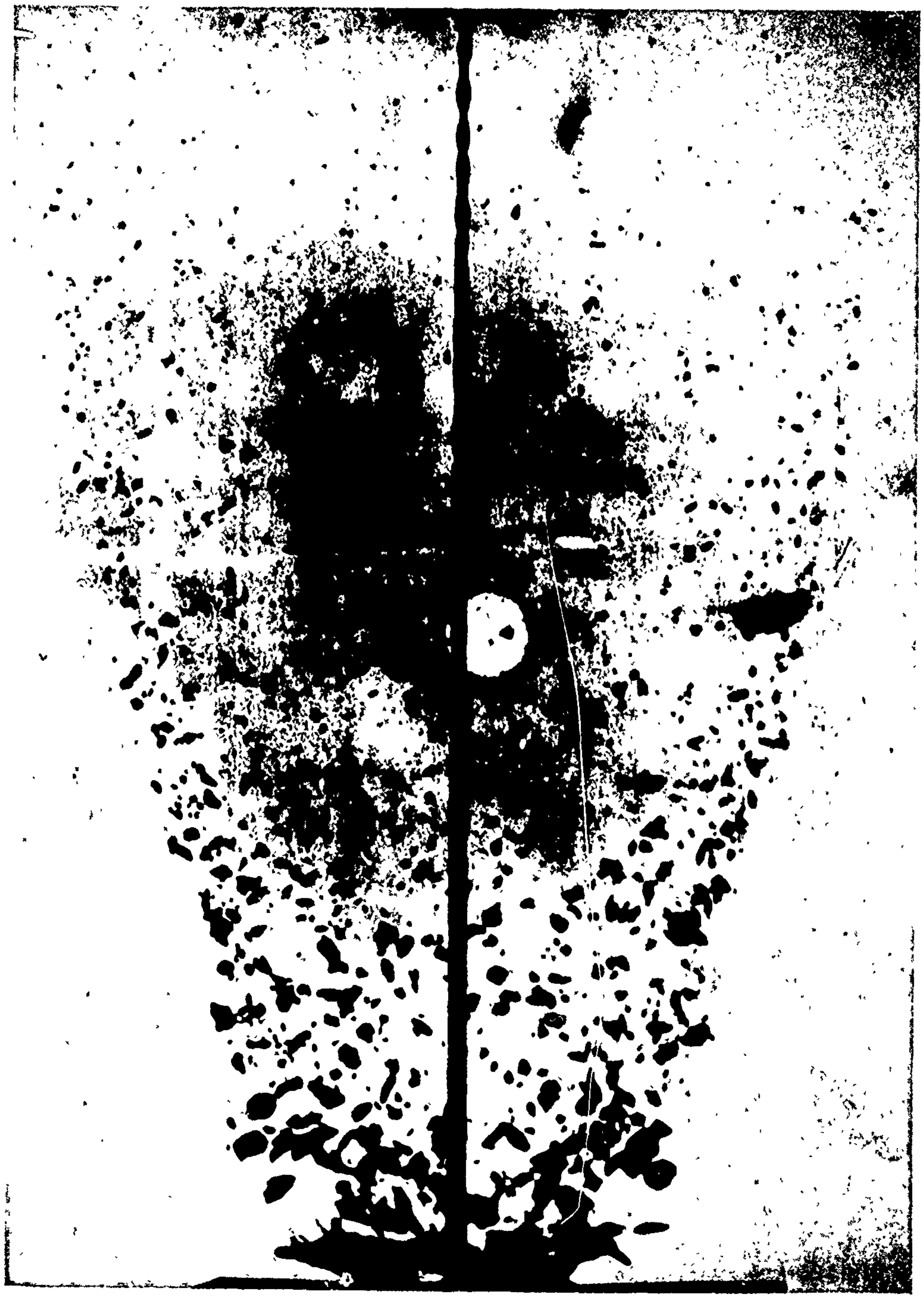


Figure 24 Spall Accompanying Jet Penetration

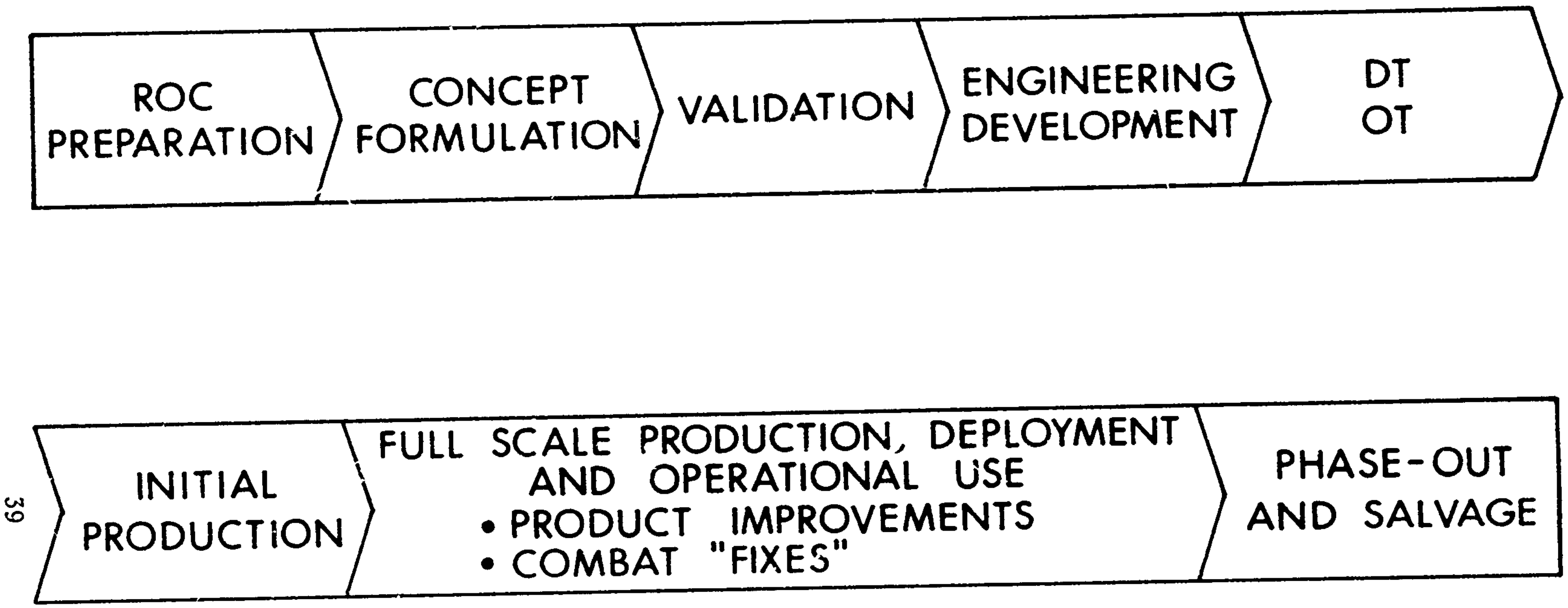


Figure 25 Life Cycle

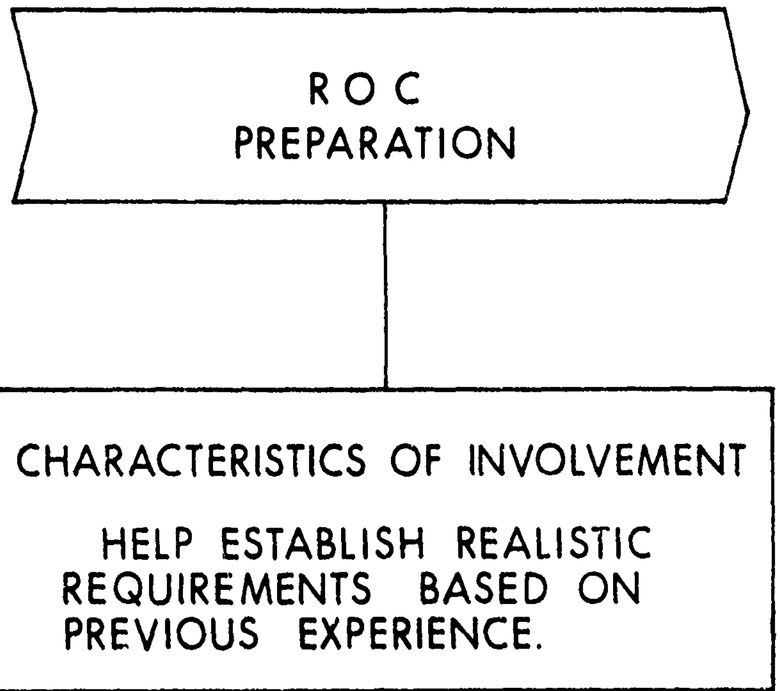


Figure 26 Life Cycle Phase

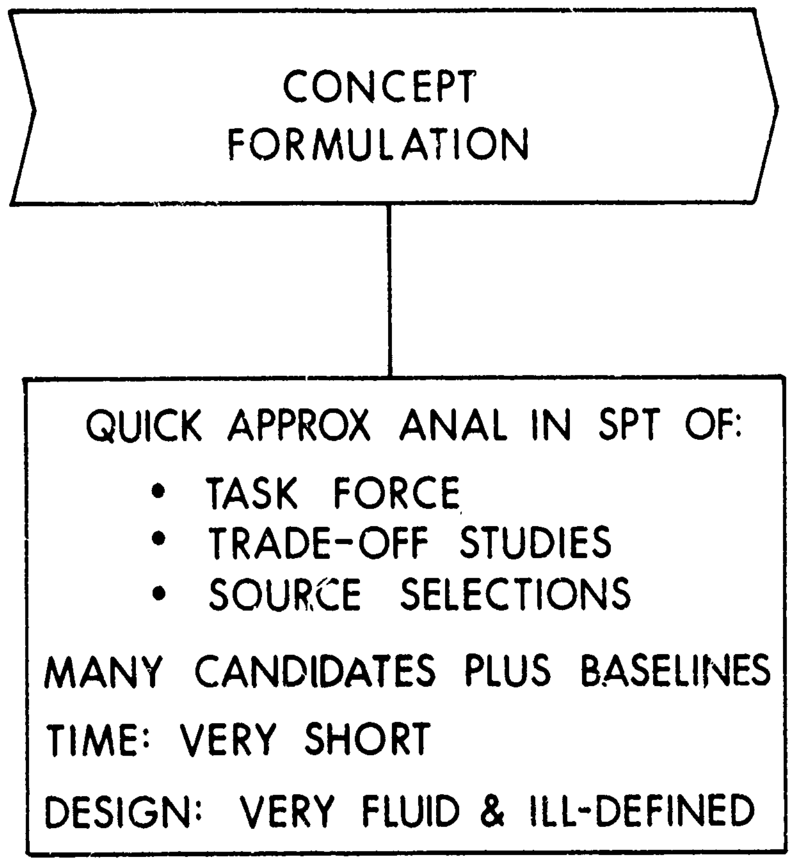


Figure 27 Life Cycle Phase

the very short time available for such studies, the large number of candidate designs which must be considered and the fluidity of the design details, these analytical studies conducted in this early phase of the development cycle are often "quick-and-dirty" with many approximations. What I mean is, that less sophistication in target descriptions and other inputs is needed to conduct the studies. Industry might well perform these vulnerability studies in order to offer more acceptible concepts from this point of view. However, to do this kind of study, the vulnerability analyst must be thoroughly aware of what kinds of approximations and simplifications he can safely make. This is why a fundamental knowledge of the more rigorous approach such as I mentioned earlier is necessary. This is the phase where new technology should be exposed and new vulnerability reduction principles introduced.

Next is Validation, Figure 28. In this phase the vulnerability analyses tend to be quick, because the time available is still short. The analysis can be somewhat more sophisticated at this stage because the design features are beginning to firm up. The questions to answer are whether or not the prototypes meet the requirements and whether additional guidance can be given for design purposes and thus allow maximum munition effectiveness or system survivability.

By the time we get to engineering development, Figure 29, we can perform the most rigorous analysis. All elements are accounted for and data can be provided for complete system evaluation. We can see at this point just how effective the vulnerability reduction features are and what possible last minute changes are feasible. Industry needs the benefit of this prior to going into testing where their hardware may be competing with others.

We are also involved in the developmental testing and operational testing, Figure 30. When deficiencies are found by TECOM*, OTEA* and others, we provide advice, as appropriate, on how the deficiencies might be remedied. Industry help is very valuable at this point. In addition, the DT/OT tests in many cases provide us an excellent source of hard input data which is needed for improvement and substantiation of our models and analytical procedures.

Hopefully, by the initial production phase most of the problems are solved, Figure 31. In this case our involvement tapers off. Usually, during production, deployment and use of a materiel item, the opportunity (or necessity) to make improvements or "fixes" arises and the vulnerability community, including industry, is frequently called upon once again for input. In this phase we also obtain, in many cases, valuable combat data, which again help us validate our methodology for vulnerability assessment and possible means of further hardening the system for increased battlefield survivability.

TECOM = U.S. Army Test and Evaluation Command, Aberdeen Proving Ground, Md.

OTEA = Operational Test and Evaluation Agency, Ft. Belvoir, VA.

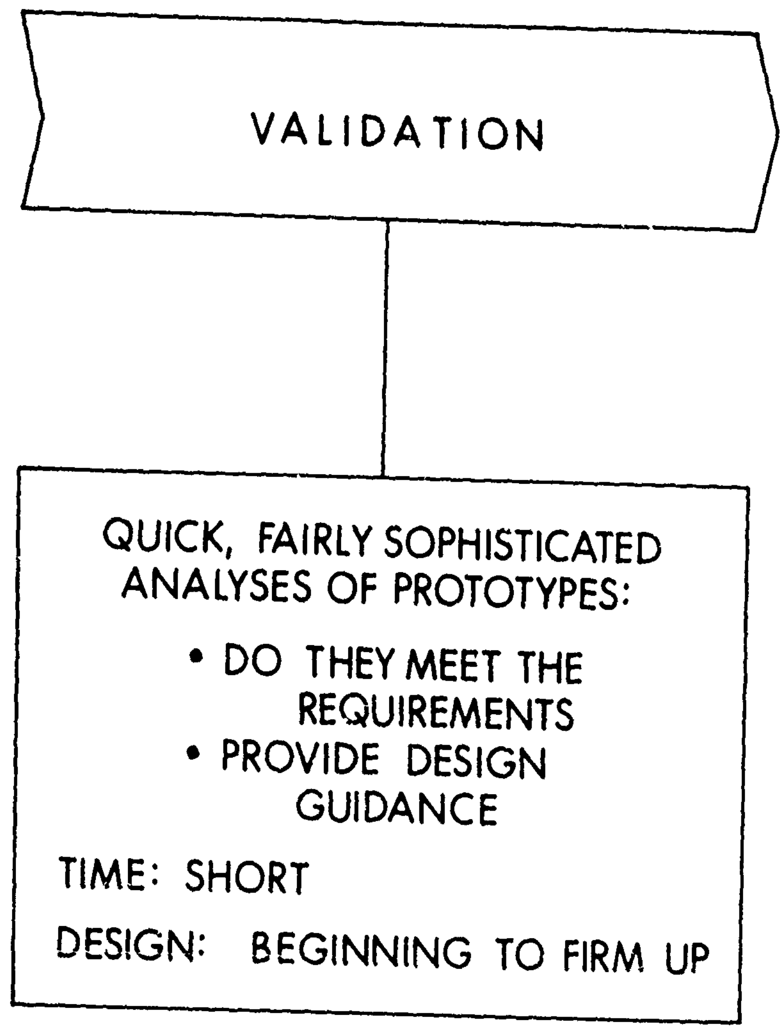


Figure 28 Life Cycle Phase

ENGINEERING
DEVELOPMENT

RIGOROUS, SOPHISTICATED
ANALYSES IN SUPPORT OF:

- SYSTEM EVALUATIONS
- DESIGN STUDIES

TIME: ADEQUATE

DESIGN: FULLY FIXED

Figure 29 Life Cycle Phase

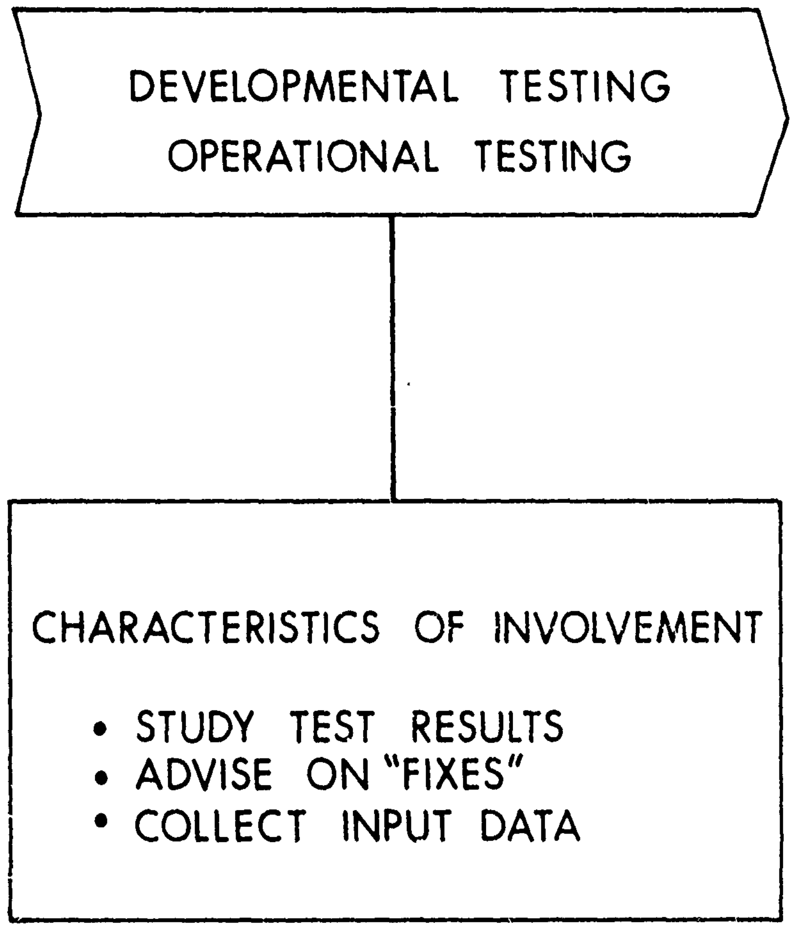


Figure 30 Life Cycle Phase

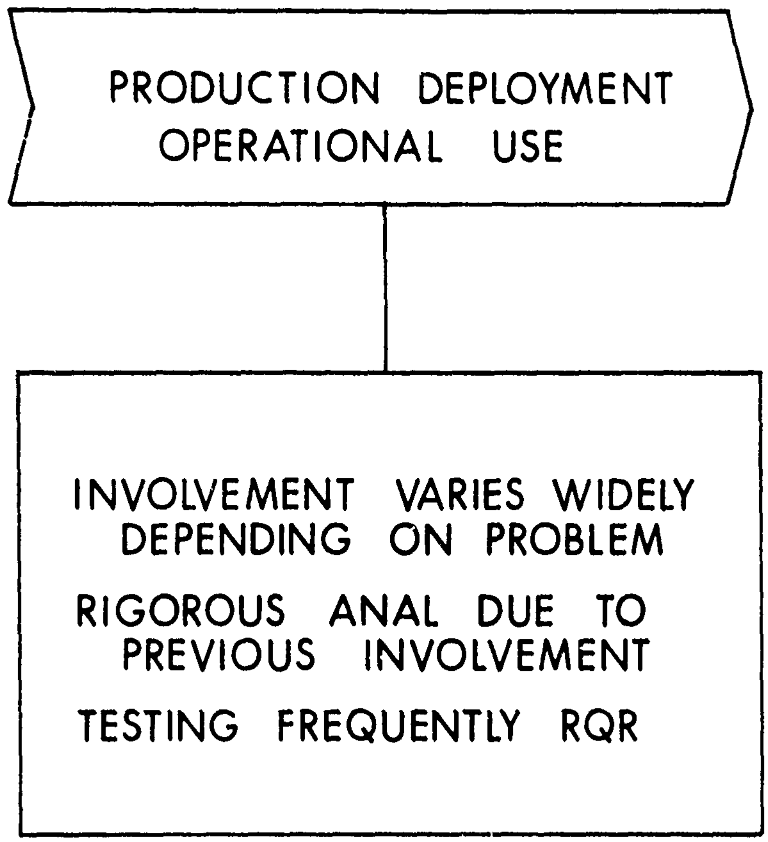


Figure 31 Life Cycle Phase

Lastly, is phase out and salvage for the materiel, Figure 32. Even when the item has reached the end of its useful life, it shouldn't lose our interest. Here we can ferret out this surplus or salvage materiel and use it as target materiel. By conducting full scale tests against such materiel, we obtain necessary input data for use with our analytical models and data to substantiate the analytical procedures.

In all of these life cycle phases, Figure 33, industry has a vital part in helping to assure the most effective or survivable military hardware. At each phase some particular type of analysis can be performed which we'd like you to consider and become familiar with.

Conclusion

In the military there are many people involved in vulnerability analysis. The Vulnerability Laboratory is the Lead Laboratory for the Army. In the Army there are also Vulnerability Analysis Teams (VATS) located at the Commodity Commands within the Army Materiel Command. The operation of the VATS will be discussed later in the meeting. The Air Force and Navy also conduct vulnerability analyses. The Army is closely associated with much of their work through tri-service working groups where efforts have been made to establish common analysis techniques and testing procedures. These efforts have reduced substantially duplication of effort since we use common data bases as much as possible.

Many people need and use the data we derive. It's used continually by systems analysts, by project managers, by operational forces and you as contractors. It's also used to provide munition effectiveness manuals for Commanders in the field and for acquisition of munition and weapon stores. Even the police, FBI and FAA require such data from time-to-time.

The benefits of these analyses are shown on Figure 34. First, it allows us to exploit known damage mechanisms for improvement of our weapons. Second, it provides a basis for optimizing weapon requirements as well as employment techniques. Third, it affords a basis for protection of our military personnel and fourth, it gives us a rationale for reducing the vulnerability of our military equipment both in the design and development process and while in operation in the field.

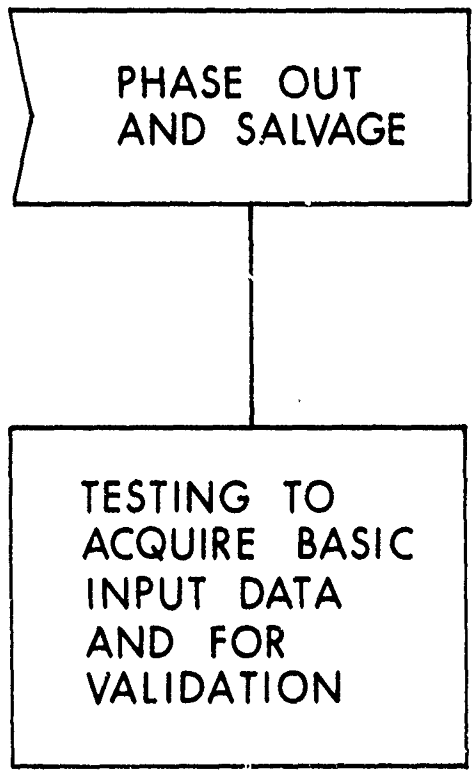


Figure 32 Life Cycle–Phases

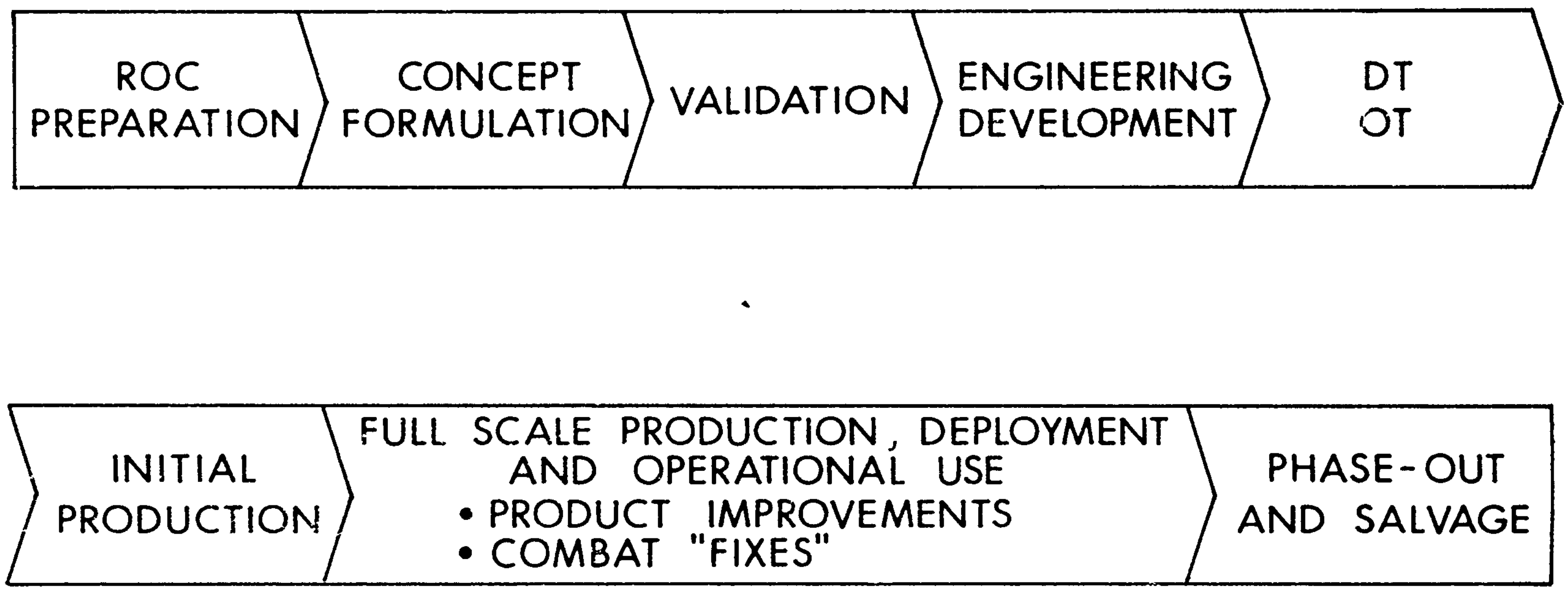


Figure 33 Life Cycle

- EXPLOIT DAMAGE MECHANISMS FOR IMPROVEMENT OF WEAPON SYSTEMS.

- OPTIMIZE WEAPON REQUIREMENTS AND EMPLOYMENT TECHNIQUES.

- PROTECT MILITARY PERSONNEL

- REDUCE VULNERABILITY OF MILITARY EQUIPMENT.

Figure 34 Advantages Derived

METHODS OF VULNERABILITY ANALYSIS

Dr. Benjamin E. Cummings

Vulnerability Laboratory

Vulnerability analysis has many shades of meaning. Survivability, lethality, vulnerable areas, failure, conditional kill probabilities... the list is long. Probability is always an essential part of the study. But the probability of "what" is highly variable. For instance consider the following expression:

$$P_K = P_D P_{H/D} P_{K/H}$$

Where P_K is the total probability of killing a target, P_D is the total probability of detecting a target, $P_{H/D}$ is the conditional probability of hitting the target given detection, and $P_{K/H}$ is the conditional probability of a kill given a hit. What part of a program defined by that expression is vulnerability analysis?

In this paper I am assuming the following meanings: the determination of $P_{K/H}$ is the vulnerability problem, $P_{H/D}$ is the delivery accuracy problem and P_D is the target detection problem. The systems analyst combines these three inputs to evaluate P_K.

There are cases in which vulnerability is not the central problem. In the case of nuclear missile submarines $P_{H/D} = P_{K/H} = 1$ is the most common assumption and so $P_K = P_D$ and detection becomes the overriding problem. As another example, in a case of overmatched targets relative to the weapon (e.g., .50 cal machine guns vs personnel) $P_{K/H}$ is again unity so $P_K = P_D P_{H/D}$; and the issue would usually separate into $P_{H/D}$ as hit probability and P_D as detection probability. However, in a more general example, all three inputs to P_K will require sophisticated analyses.

Obviously $P_{K/H}$ must be the result of: (1) defining the target, (2) defining the attack, (3) defining what constitutes a kill and (4) defining what constitutes a hit. It is the role of vulnerability methodology to provide mathematical, computer, or engineer procedures for accomplishing these four definitions and by implementation of the technical procedures turn the definitions into numbers.

As an example let us consider elephant hunting. The definition of a kill is that the elephant shall not be able to charge a total distance of 25 meters after a single hit with the projectile that constitutes the attack. We obtain intelligence estimates that an elephant can accelerate to full speed in 3 seconds and that full speed is 26.8 m/sec. Therefore, death before 2.4 seconds of elapsed time after wounding is the kill criteria. We determine that only weapons of .458 cal. or larger are legal for hunting elephant. We are informed by the Safari Analyses, Materials & Systems Agency (SAMSA) that only jacketed bullets having the characteristics shown in Table I will be available.

TABLE I

Acceptable Elephant Bullets

CAL	DIAM(m)	WEIGHT (Kg)	MAX VEL (m/sec)
.458	0.0116	0.0324	412
.458	0.0116	0.0486	275
.458	0.0116	0.0583	229
.600	0.0152	0.0583	229
.600	0.0152	0.0875	153
.600	0.0152	0.0933	143

The maximum velocity being limited by the influence of shooting accuracy on shoulder weapon recoil.

Because no prototype elephants are available for test, terminal ballistics and wound ballistics data on other targets will be used to estimate the effects of the above listed projectile-velocity combinations to produce the necessary kill.

It is determined that only a brain injury of a massive type will create the required kill. A drawing of the typical elephant skull is obtained and sent to a contractor who produces a combinatorial geometry description for use on the BRLESC II Digital Computer. A vulnerable area program as defined by the flow chart is then applied to the elephant vulnerability. The variations in skull thickness, bullet retardation and mass-velocity combination are included and the following vulnerable area distribution is obtained (Table II).

TABLE II

Vulnerable Areas for Elephant K-Kill

CAL	WEIGHT (Kg)	VELOCITY (m/sec)	VULNERABLE AREA (m^2)
458	.0324	412	0.1262
458	.0486	275	0.0842
458	.0583	229	0.0701
600	.0583	229	0.0409
600	.0875	153	0.0208
600	.0933	143	0.0182

The numbers of course are ficticious, but the process is representative of what must be done to obtain a vulnerable area table for a target/attack combination.

Figure 1 shows the steps taken to arrive at vulnerable area values. Each of the blocks marked with an "F" is a part of the feeder program which assembles the component parts of A_V analysis. As such these pieces are the bookkeeping aspect of the calculation and are a single program. The blocks marked with an "M" constitute major components of the program. Each of these blocks is of the same order as the overall feeder program. While this process seems straight-forward, the execution of details associated with the major blocks of the program require major investments of manhours, experimental work and computer hours.

The nature of a vulnerable area calculation is binary. That is, for each single shot line the calculation yields either a kill or no kill. And either all of or none of the associated area is added into the total A_V for that shot line. A modification of this approach, which provides an ad hoc correction to the binary approach, is to multiply the associated area by a conditional kill probability to obtain a reduced contribution to the vulnerable area. The next step in the direction of a continuous model of vulnerability is a chain or weakest link model.

If N necessary components of a system all must function in order for the system to be "alive" (not killed), then the kill probability for the system is

$$P_K = 1 - \prod_{i=1}^{N} (1-P_{K_i})$$

where $(1-P_K)_i$ is the probability that the i^{th} component is not killed. That is, the above expression is the probability that at least some component fails and thus causes the total system to fail.

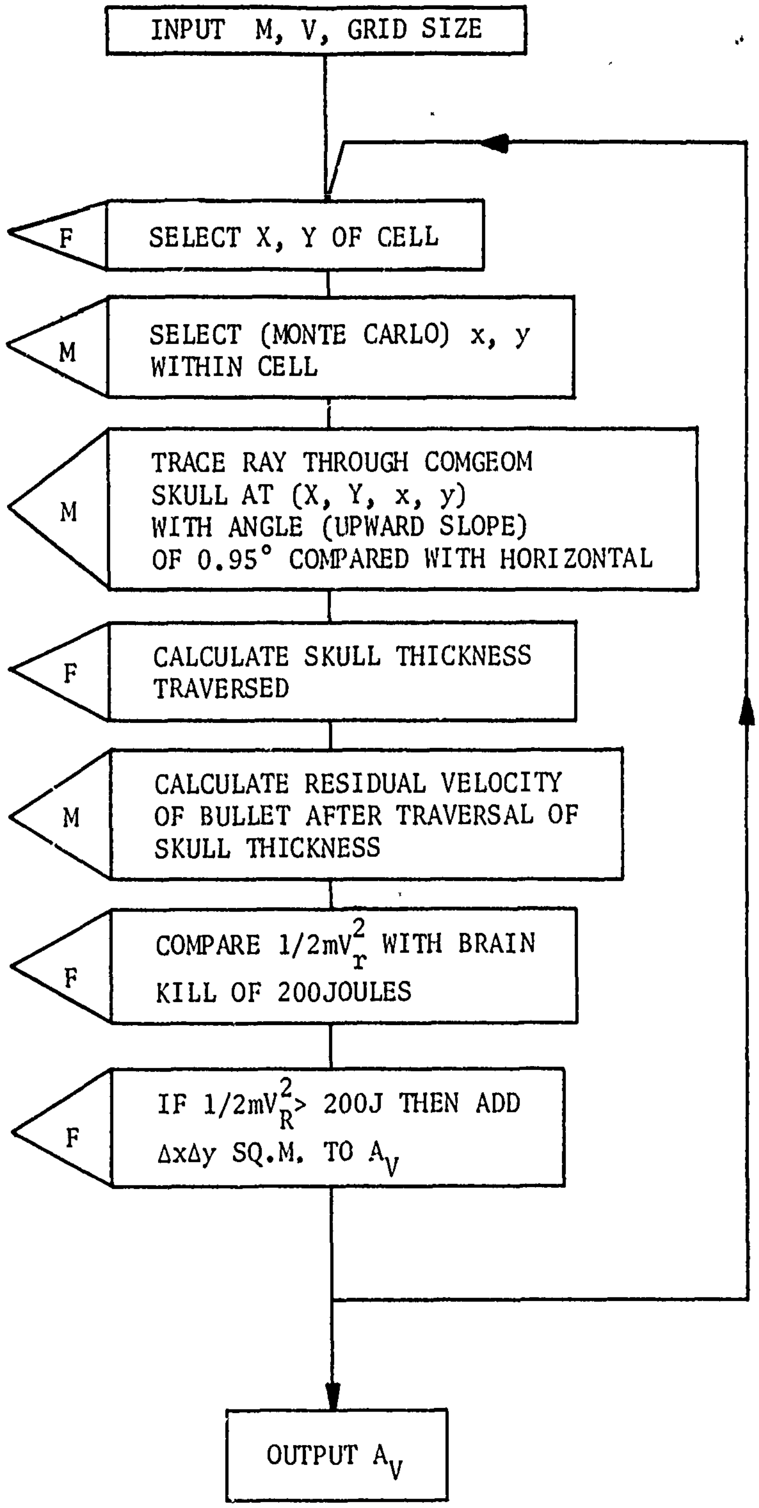


Figure 1. Flow Chart for Arriving at Vulnerable Area Values

For example, loss of a track will cause a mobility kill on a tank.

This innocent looking little equation can beget immense computer codes and large if not monumental expenditures of manhours on computational effort.

A case in point is the newly developed AVVAM(Armored Vehicle Vulnerability Analysis Model) The summary flow chart for the AVVAM shows a simple process, but simple in this case is not computationally simple. The computer code that represents the target description is complex. Many repetitions of the system sub routines.... 3 to 5 million calls of subroutines in a typical case, are required.

AVVAM is a conceptual model and associated digital computer code developed at BRL to analytically assess the vulnerability of armored vehicles. AVVAM can be employed to perform both armored vehicle vulnerability and antiarmor weapons design and analysis studies. This version of AVVAM treats internal components and personnel subjected to penetration and/or perforation damage mechanisms. The attacking munition may be a shaped charge, kinetic energy projectile or a Misznay-Schardin land mine. With additional effort the present model may be extended to include external component damage and other damage mechanisms. Although originally developed for armored vehicles, the code is not restricted to armored vehicles - it may be employed to assess the vulnerability of any structure.

AVVAM is an outgrowth of an existing digital computer code developed by the Surface Targets Branch, Vulnerability Laboratory, BRL. AVVAM is based on analytical evaluations of the damage inflicted on individual critical components and the aggregate effect of these damaged components on compartment and overall vehicle vulnerability. To do this, AVVAM accounts for not only the damage inflicted on components in the direct line of fire (shotline) of the attacking munition but also the damage inflicted by armor spall and/or munition fragment sprays on components located away from the munition shotline. AVVAM also accounts for the degrading (or possibly enhancing) effects of the spall and/or fragment sprays caused by components positioned between the armor and the critical components.

The code consists of two major, individual codes. One code is concerned with the vehicle geometry and configuration and the components in the vehicle critical to its operation. The other code is concerned with the terminal ballistics and behind-the-armor effects of the attacking munition as well as the assessment of kill probability. Separation of these functions in this manner facilitates design optimization and systems analyses studies. Target vehicle parameters and/or munition parameters can be varied with relative ease. A series of munition design iterations or whole weapons systems intended to defeat a given target vehicle can be processed and evaluated by AVVAM to achieve an optimum design. On the other hand, a similar iteration process can be followed in the optimum design of

an armored vehicle. In this latter process a whole variety of armor materials and configurations as well as internal components and their character, configurations, and locations may be processed and evaluated until an optimum conbination is achieved.

To generate the target description information, AVVAM employs the GIFT (Geometric Information for a Target) code. This GIFT code is an improved version of the existing MAGIC code. The identification, location and presented area determinations of critical components and the intervening component information is generated by a new subcode recently developed at BRL called RIP (Rays Initiated at a Point).

The second major code employed in AVVAM encompasses the terminal ballistics of the attacking munition and the post-plate-perforation (P^3) characteristics of plate spall or munition fragment sprays. In addition, this second code calculates the vulnerability of selected components within the vehicle as well as compartment vulnerability and overall vehicle vulnerability.

In operation, AVVAM selects critical components within the target and then evaluates the extent of damage and kill probability for each selected munition aim point in a given view of the target. It does this by determining the armor thickness in the direction of the attacking shotline of the munition, the number of interceding components between the vehicle armor and the critical component and then utilizes the behind-the-plate characterization of a specific munition to calculate maximum, mean, and minimum kill probabilities given a hit for all or selected critical components within the vehicle. This whole process is accomplished by firing a large number of parallel rays at a given attack angle and azimuth into the target. Each individual parallel ray then spawns new rays that are initiated at the munition exit point on the armor interior surface. These new rays are used to search out the vulnerable components, define their position, shielding, and presented area. Then the post-plate-perforation subcode, converts terminal ballistics input data into an expected number of hits into each of the vulnerable components and finally the C^3PKH* subcode determines the probability of a kill of these components for the expected number of hits. The kill probabilities for all the vulnerable components within a given compartment are combined into compartment M, F, & K* kills. In addition, overall values for M, F, & K kills of the whole vehicle are also determined.

A flow chart summarizing the operations of AVVAM is presented by Figure 2. In this Figure Box 1 represents the target input. Box 2 is the RIP section, Box 3 is the P^3 section and Box 4 is the C^3PKH section. The C^3PKH section provides the output in terms of probability of a kill given a hit. Also indicated in the figure is Box 5 which indicates an interation scheme that may be employed for multiple views. Since the sections represented by Box 1, 2, 3, and 4 provide the PK/H output for a single view, results for multiple views may be obtained by interating between Boxes 2, 3, and 4 for each view desired.

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*See Figure 2.

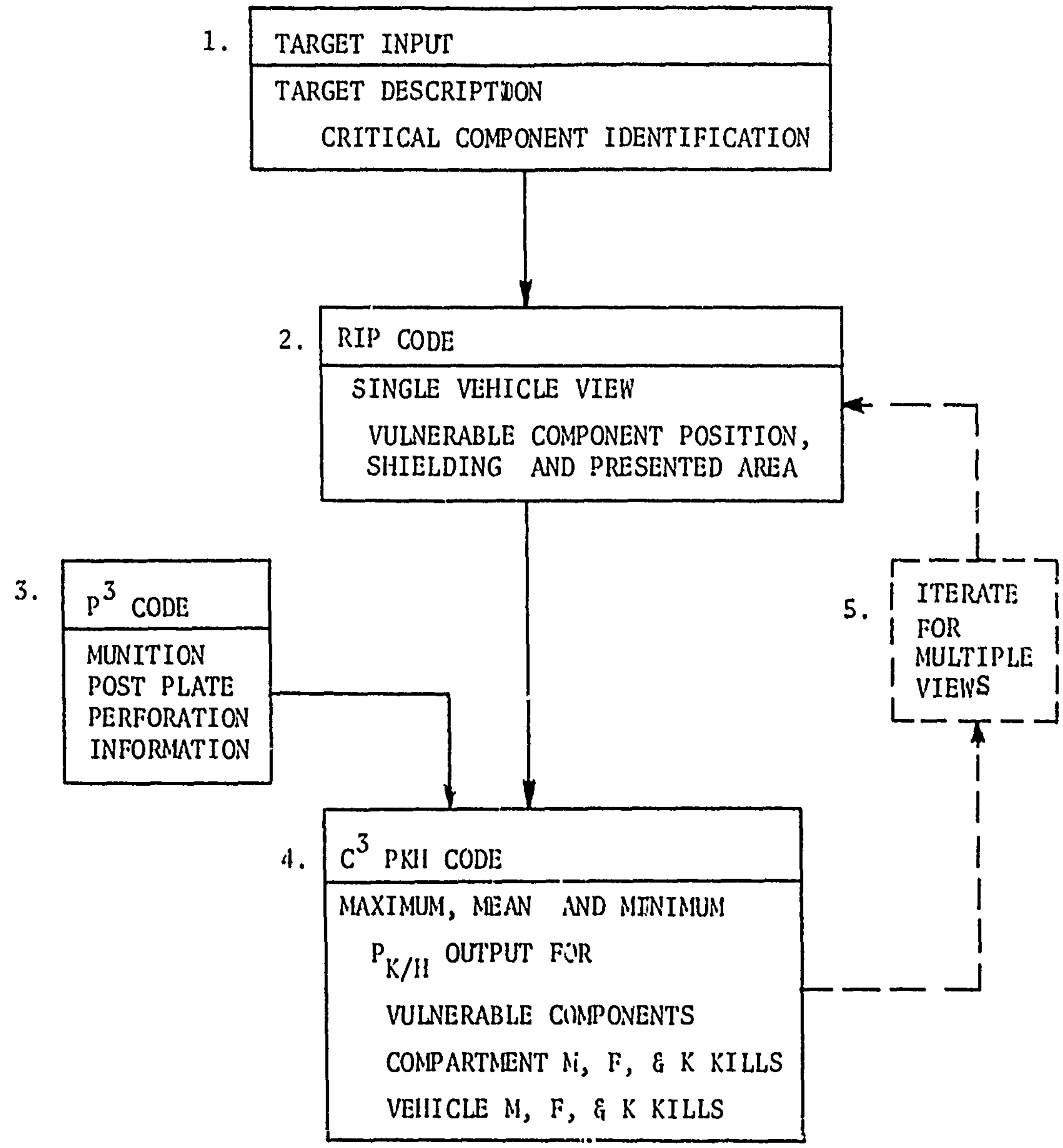

Figure 2. AVVAM-1 Code Summary Flow Chart

The code operates as follows: The particular target description is inputed through Box 1 on cards and the specific munition is inputed by cards through Box 3. Information for the P^3 section is handled by card input. After the target is described and the critical components identified, RIP then, for a single vehicle view, selects a starting point on the vehicle, fires a main ray at the starting point, and essentially determines the position, shielding, and presented area of all the critical components in the vehicle in relation to the shotline of the main ray, Figure 3. The C^3PKH code, Figure 4, calls on the Post-Plate-Perforation code to supply the behind the plate spall data and main munition shotline information to include number of fragments, size, and speed of fragments. Next, it calculates the expected number of fragments to hit a given critical component, and then the probability of killing that component given a hit. It does this for each critical component identified by the RIP code for the particular shotline selected. All the critical components are evaluated for the first shotline. The mean, and the minimum probabilities of a kill given a hit are calculated for all the components in the view of the new shotline. This process is continued until the whole view of the vehicle is completed. At this point the output of the AVVAM code is the following: Maximum, mean and minimum probability of a kill for each critical component in the vehicle, a set of compartment M, F, & K kill probabilities and overall vehicle view probability of M, F, & K kill values. During these calculations the C^3PKH code in conjunction with the P^3 code account for the mass and velocity attrition of the shotline and spall fragments as they perforate intercedent components between the exit point on the armor and the specific vulnerable component under evaluation at the time.

To this point we have seen how vulnerable areas and target kill probabilities may be calculated. There remains a large number of functions performed by the vulnerability analyst. For instance, it is necessary to find out what the penetration capacity of a given projectile is in attacking a target. As stated this is almost a task for the terminal ballistician; however, the engineering emphasis as opposed to the scientific emphasis makes it a vulnerability problem. Over the past several years the VL has developed a number of simplified vulnerability computer codes for use on desktop calculators. One of these is documented in BRL MR 2366. This program is an example of the necessary "attack data" preparation that constitutes a significant part of the workload for a vulnerability analyst.

Specifically, this code (based on the Project Thor penetration equations for steel fragments) predicts: (a) the residual mass and residual velocity of the largest and fastest fragment that exists after perforation of a single target layer, (b) the minimum striking velocity required by a fragment to perforate a given target layer with a required residual velocity, (c) the maximum obliquity angle at which a fragment may perforate a given target layer with a required residual velocity, (d) the residual mass and the residual velocity of the largest and the fastest fragment that exists perforating a spaced target array, and

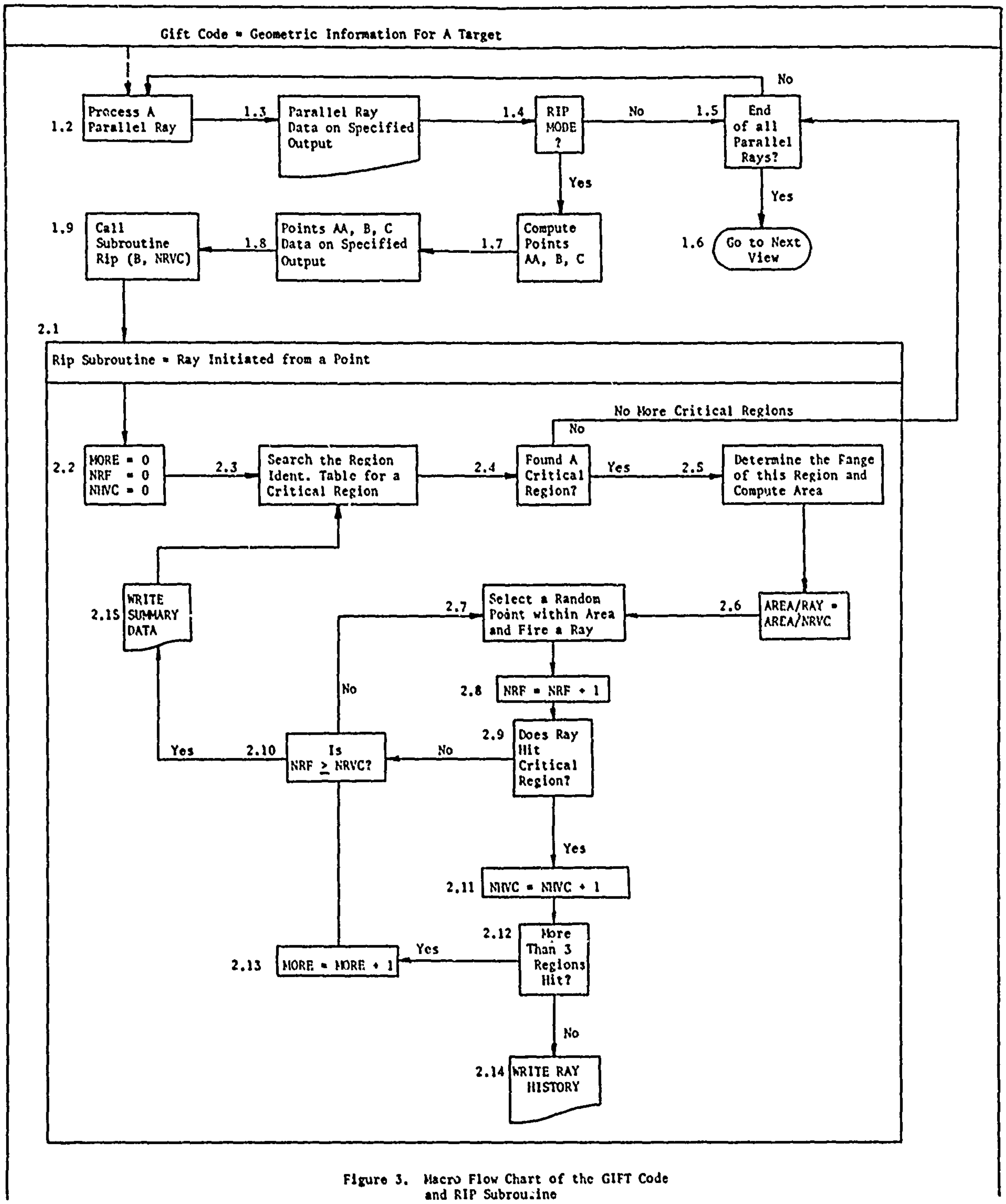

Figure 3. Macro Flow Chart of the GIFT Code and RIP Subroutine

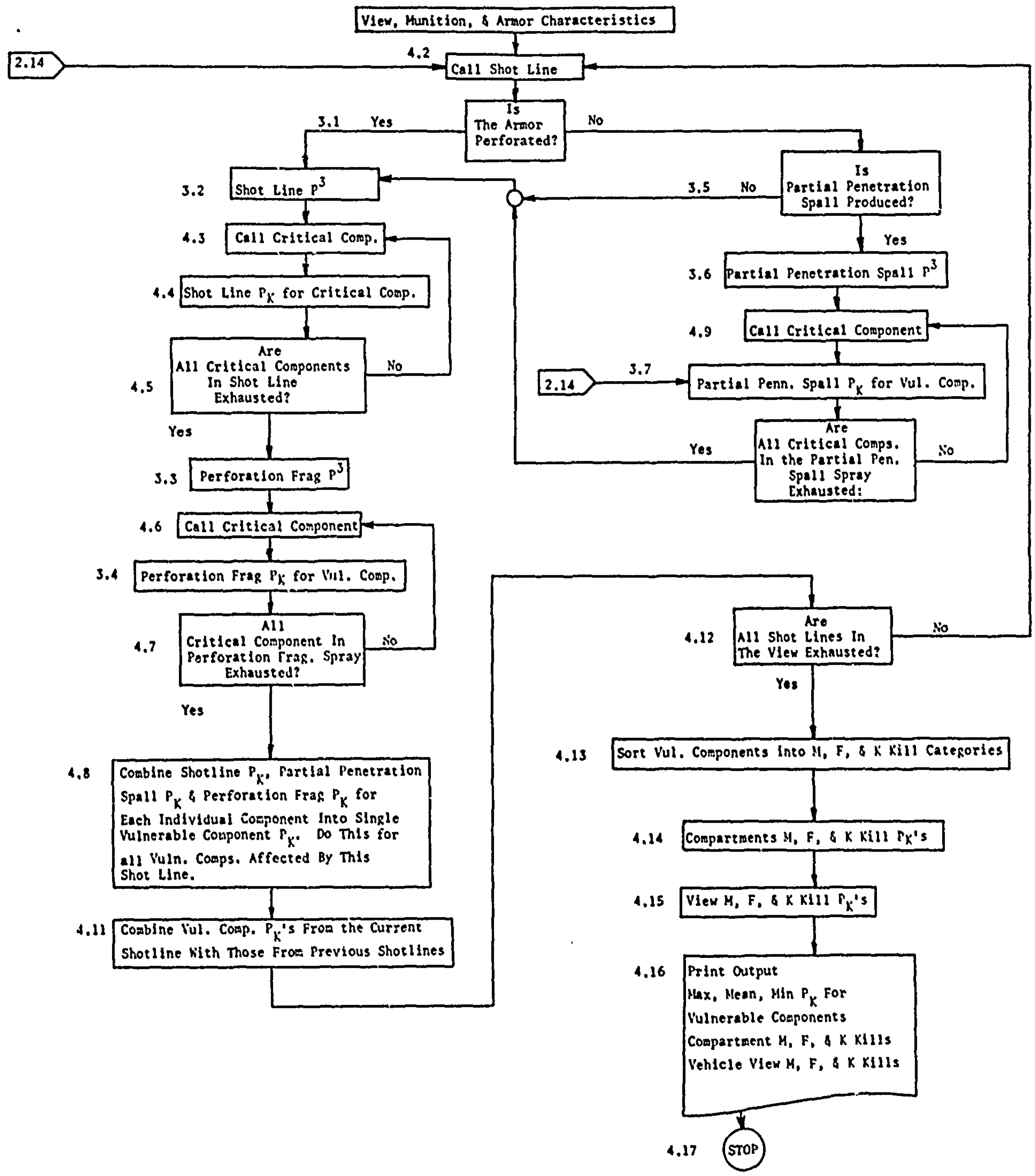

Figure 4. (U) P^3 and C^3PKH Flow Chart

(e) the fragment striking mass and striking velocity required to give a desired residual mass and residual velocity for a fragment after perforating the last layer of a spaced target array. The form of the equations used to fit the data for penetration is

$$Y_R = Y_S - 10^c (tA)^{\alpha} M^{\beta} (\mathrm{SEC}\,\theta)^{\gamma} V_S^{\lambda}$$

where t= target thickness
m= striking mass
A= presented area of striking mass
θ= angle of obliquity at impact
Y_s= either striking velocity or striking mass
Y_r= either residual velocity or residual mass

and $c, \alpha, \beta, \gamma, \lambda$, are parameters used to optimize the agreement between the equation and experimental data. This is an Ad Hoc solution to a difficult problem requiring an immediate answer. It is representative of many problem areas in which the VL must work. The characteristics are: (1) no adequate scientific base exists for creating a predictive theory, (2) the data base does not span the domain for which application must be found, (3) the data base is not adequate for statistically valid fitting of the data, and (4) there is neither time nor staff to obtain either the scientific or statistical base needed. Naturally, experience plays the important role in such problems and usually the results have been acceptable.

One reason that such short notice rapid response problems have been handled successfully is because many aspects of a given problem can be used to provide limits to the analysis of a given problem. By the nature of quick response problem, i.e., time urgency, they are usually classified. So let us consider an unclassified example which may illustrate the ways engineering can lead to vulnerability estimates.

Suppose we wish to know what the correct weapon size would be for clearing mine fields. We propose that blast overpressure or impulse from either nuclear or conventional explosives will be used, but not mixed, i.e., only H.E. or only nuclear, then the scaling laws for yield and cost will apply within the class.

The area attack (sanitized) by a given number, n, of these weapons will be

$$A = n\pi R^2$$

where R= the sanitized radius. The overpressure scaling relation is

$$\frac{R(W)}{R_0} = \left(\frac{W}{W_0}\right)^{1/3} \qquad \text{or} \qquad R = R_0 \left(\frac{W}{W_0}\right)^{1/3}$$

and $$A = n\pi R_o^2 \left(\frac{W}{W_o}\right)^{2/3} = K\,n\,W^{2/3}.$$

In selecting a weapon yield, cost, S, may be a significant factor and we may reasonably assume it to be represented in the form

$$S = S_o + \beta W^{\alpha} \quad \text{or}$$

$$W = \left(\frac{S-S_o}{\beta}\right)^{1/\alpha}.$$

and hence the cost to area relation may be obtained in the form

$$A = Kn\left[\left(\frac{S-S_o}{\beta}\right)^{1/\alpha}\right]^{2/3} \quad \text{or}$$

$$A = Kn\left(\frac{S-S_o}{\beta}\right)^{2/3\alpha}.$$

Now the vulnerability of the mine field has been priced area per dollar basis but that is <u>not</u> enough. The resources available must be based on a fixed cost, $C=nS$ but

$$n = \frac{A}{KW^{2/3}} \quad \text{so} \quad C = \frac{A}{Kw^{2/3}}\left(S_o + \beta W^{\alpha}\right).$$

For convenience let us assume $S_o << \beta W^{\alpha}$ then

$$C = \frac{A\beta W^{\alpha}}{K\,W^{2/3}}$$, which yields three cases

$\alpha<2/3$, $\alpha = 2/3$, $\alpha>2/3$. The first case yields $(C/A) \sim \frac{1}{W^{\gamma}}$ with $\gamma>0$.

This gives a payoff for large yield weapons. In the second case, $\alpha = 2/3$ C/A is independent of yield. In the third case $\frac{C}{A} \sim W^{\gamma}, \gamma>0$.

Thus, there is a cost benefit from small yield weapons.

Of course, the analysis looks like a study of cost effectiveness rather than vulnerability. But it follows exactly the same principles as would be applied in a vulnerability analysis in which dollars are the weapons and area is the target. That is, "A" becomes the vulnerable area and "W" the weapon resource with α classifying three separate weapons. The analysis is, of course, deterministic. There is merit in examining another simple but non-deterministic problem. Suppose, for instance, that we have a target made of an elastic-perfectly-plastic material whose force displacement relation gives linearly increasing displacement with increasing force up to yield and then increasing displacement with constant force up to rupture. For displacements less than rupture the unloading path is parallel to the linear elastic load path. Then upon reloading the material behaves as if the deformation required to cause rupture had been reduced by the amount of the original load/unload path, Figure 5. This might be the case of a blast loaded building.

The loading due to each blast in a series of attacks may be less than that required to destroy the target in a single attack, but their progressive damage may lead to eventual failure.

The analysis determining the possibility of progressive destruction of targets must find the change in load-carrying capacity of the target as a function of the previous history of loading.

In a design which can be treated by the analysis presented here the load-carrying characteristics of the target must be modeled by an elastic-linear-plastic, one-degree-of-freedom oscillator. Many cases of importance occur in a regime of loading and design such that the duration of the positive phase of overpressure loading is long compared with the period of vibration of the target. For such targets and loadings the approximation of the loading becomes relatively independent of the duration of the positive phase, and a step function becomes an adequate approximation of the loading history which can be used with little influence on the evaluation of the response. With these assumptions, we idealize to a step-function loading applied to a single-degree-of-freedom oscillator having a bilinear spring characteristic. The loading that will introduce failure of the bilinear spring depends on the failure criterion assigned. If the criterion is that the elastic limit shall not be exceeded, then the step-function that causes a deflection equal to the yield-point, x_y, is the failure criterion. On the other hand, if the failure criterion is at rupture, it will be necessary to obtain a deflection equal to the ultimate elongation x_u. A straight-forward way of obtaining the relationship between the step-load of amplitude A and the response of the system is to equate the external work done on the system to the energy stored in the system. This is the technique frequently used by Haskell[15] and others in determining the maximum damage that can be imparted to a structure by a given energy flux attack. There is a tacit assumption associated with this form of

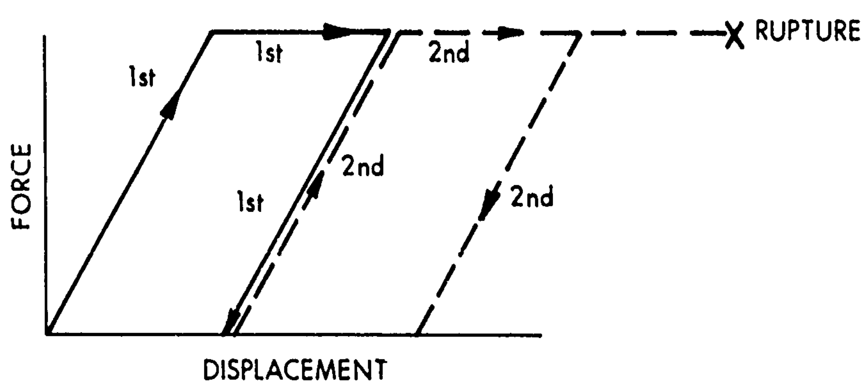

Figure-5 Assumed Force-Displacement Relation

analysis to the effect that the energy of motion of the structure ends up in deformation energy at the time when all motion stops. The maximum size of the possible error is equal to the energy in the elastic (pre-yield) part of the force-displacement diagram, or

$$\frac{1}{2}(x_y)^2K, \text{ as shown in Figure 6.}$$

The problem is to determine the minimum-amplitude step-load that will cause the deflection to be greater than that at ultimate failure. For convenience of analysis, the force-versus-displacement function is normalized. The normalization is achieved by setting both the force and displacement at the yield point equal to unity, and by taking m as 1. The equations of motion are:

$$m\ddot{x} + Kx = Af(t) \quad \text{for} \quad |x| < |x_y|$$

$$m\ddot{x} + \alpha Kx = Kx_y(\alpha - 1) + Af(t) \quad \text{for} \quad |x_y| \le |x| \le |x_u|$$

or in normalized form

$$\frac{d^2§}{d\tau^2} + § = \frac{A}{Kx_y} f(\frac{\tau}{\omega}) \quad \text{for} \quad |§| < 1$$

$$\frac{d^2§}{d\tau^2} + \alpha§ = (\alpha - 1) + \frac{A}{Kx_y} f(\frac{\tau}{\omega}) \quad \text{for} \quad 1 \le |§| \le \mu$$

where

$$§ = x/x_y \quad , \quad \tau = \omega t \ , \ \omega = \sqrt{K/m}$$

$$\mu = x_u/x_y$$

For the energy-work integral of the equations of motion to be valid, the kinetic energy term must vanish when the displacement reaches the failure level--otherwise the minimum input would not be obtained. When the integral is taken and the terms rearranged for convenient presentation, the result is

$$\frac{A}{Kx_y} = \frac{2\mu - 1}{2\mu} + \frac{\alpha}{2}\frac{(\mu - 1)^2}{\mu}$$

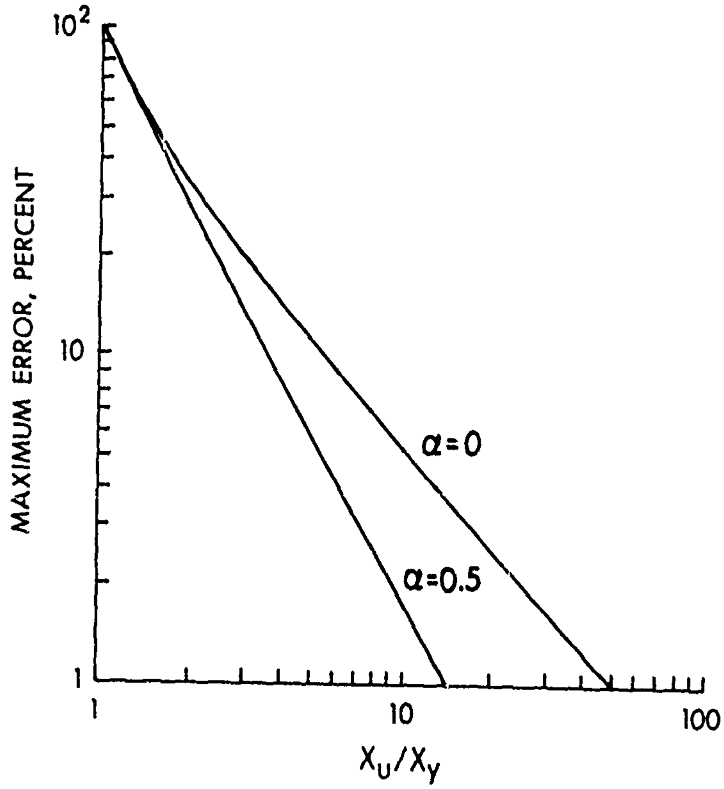

Figure 6 Maximum Error

In the analysis of the bilinear response, it is convenient to refer the applied forces to the force required to produce a displacement at the onset of yield. This preferred reference is the largest step function that will produce no permanent reduction of the load carrying capacity of the bilinear system. This limiting load for the damage condition is found from the previous equation by first setting the bilinearity parameter α equal to unity (which results in a linear force displacement law) and then setting the displacement parameter μ equal to unity (which produces a displacement equivalent to the yield condition) to give

$$\frac{A_y}{Kx_y} = \frac{1}{2}$$

The load ratio between ultimate failure, $x = x_u$, and incipient failure is obtained as $A/A_y = L$, or

$$L = \frac{2\mu - 1}{\mu} + \frac{\alpha(\mu - 1)^2}{\mu} \quad , \mu > 1$$

This formula is for the ultimate failure deflection, but it could be used, as well, for any deflection greater than yield. When put in that form, it is useful in calculating partial damage to the structure.

$$L_§ = \frac{2§ - 1}{§} + \frac{\alpha(§ - 1)^2}{§}$$

We must associate a value of P_k with yield and ultimate displacements. For the present let us consider targets that are amenable to brittle failure theory. Cummings & Williams[16] have recently obtained a probability of failure expression which should be applicable to structures in the form

$$P_f = 1 - \mathrm{EXP}\left(-\frac{V}{V_o}\left[\frac{E}{E_o}\right]^6\right)$$

Where V/V_o is the influence of volume and E/E_o is the influence of work done on the structure compared with its energy storage capacity at rupture. For our problem it is reasonable to assume fixed volume and replace V/V_o with a number such that the probability of failure has a fixed value at $E=E_o$. For this purpose, it is assumed that $P_f(E=E_o) = 0.99$, although any value <1 could be chosen. Then following the brittle fracture model

$$P_f = 1 - \mathrm{EXP}\left(-4.61\left(\frac{E}{E_o}\right)^6\right) .$$

Now we have a conflict of sorts, in that the failure model is derived from linear elastic theory and it is being applied to a material characterized by a non-linear, non-elastic force response curve. The justification is only that one would arrive at the same kind of expression by proceeding from first principles through a probability argument. We will work out a specific example. First assume that the model of brittle failure is amenable to some inelastic deformation, say $\mu=2$. Second assume that $\alpha=0$, i.e., a "plastic" kind of elongation past yield.

We calculate the initial energy storage capacity E_o as

$$E_o = (\text{Elastic Energy}) \left[(1+2(\mu-1)+\alpha(\mu-1)^2\right]$$

or $\frac{E_o}{E_e} = 3$. For the first attack we consider a load ratio, L, of 4/3 which corresponds to a deformation, ξ, of 1.5. The energy ratio is

$$E_1/E_o = 2/3 \text{ and}$$

$$P_{NF}^{(1)} = 0.667, \; P_F^{(1)} = 0.333.$$

If failure did not occur, then the residual strength is determined by

$\mu_2 = \mu_1 + 1 - \S_1$ or $\mu_2 = 1.5$ and the residual energy storage capacity

is $(E_o/E_e) = 2$. Consider a second attack of $L = 1.3$ then $\S_2 = 1.43$, $(E_2/E_e) = 1.86$, $(E_2/E_o) = 0.930$ and $P_{NF}^{(2)} = .051$. But we wish to know the probability that the target failed at least once in the two attacks, i.e.,

$$P_F^{(2)} = 1 - P_{NF}^{(2)} \, P_{NF}^{(1)} = 1 - (0.051)(0.667) = 0.966$$

If failure did not occur then the residual strength will be

$$\mu_3 = \mu_2 + 1 - \S_2 = 1.07 \text{ with } E_o^{(3)}/E_e = 1.14 \text{ or only}$$

57% of the original value.

All of the problems of vulnerability stand separated from each other because they are solved by ad hoc devices. But as a final example we append this flow chart, Figure 7, which typifies the interaction of ad hoc techniques to achieve a real world solution.

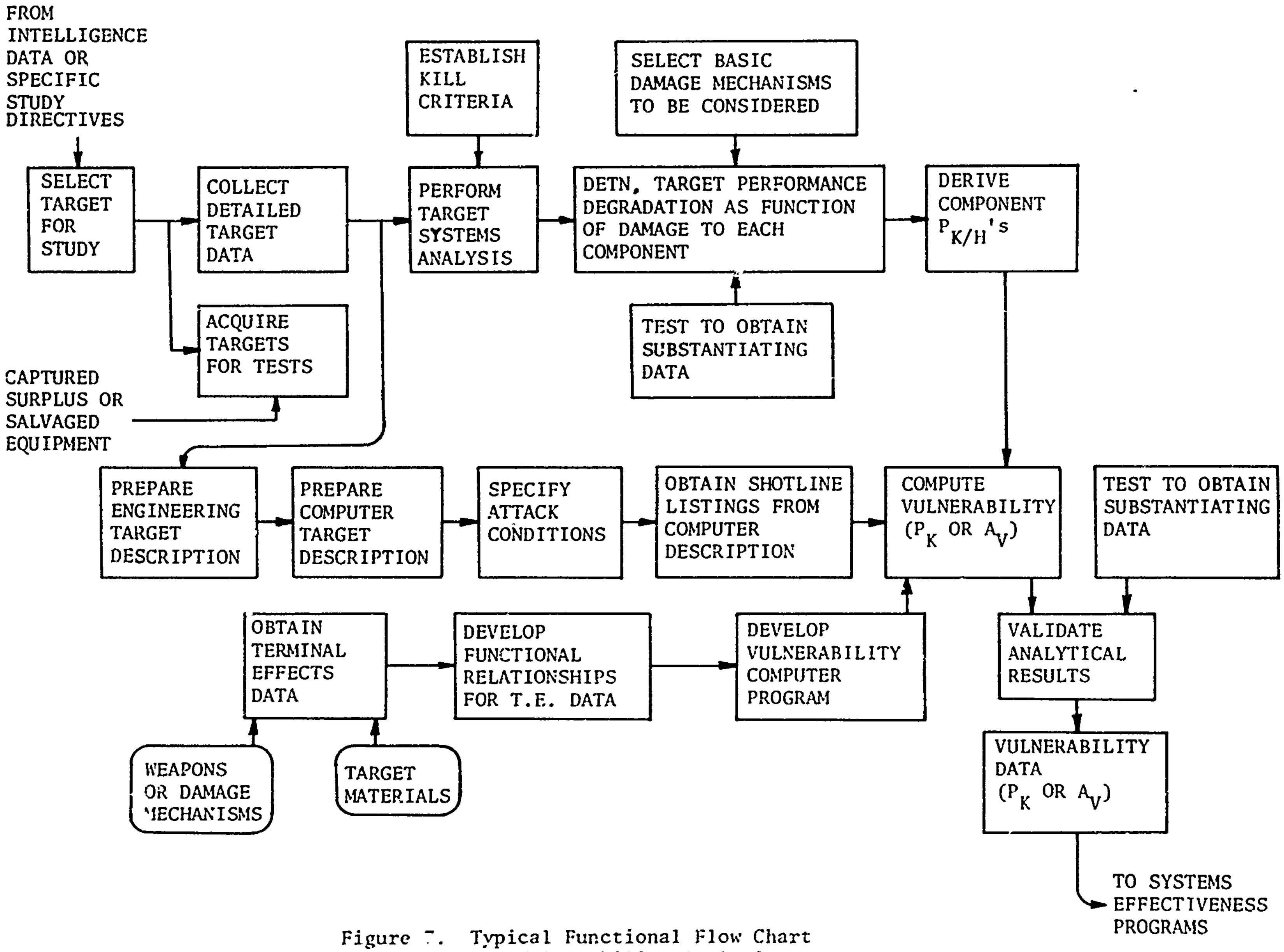

Figure 7. Typical Functional Flow Chart For Vulnerability Analysis

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VULNERABILITY REDUCTION PRINCIPLES

Walter S. Vikestad

You should have a good idea from the previous presentations of what vulnerability is and what methodologies are available to you so that you can determine the vulnerability of a system. I would like to discuss the subject of vulnerability reduction. Now unfortunately, the first thing that comes to mind for many people is, hang a piece of armor on it and that will take care of the vulnerability - if it doesn't weigh too much or if it doesn't get in the way. There is much more to vulnerability reduction than simply hanging a piece of armor on some brackets. Vulnerability Reduction has to be treated as a discipline, (Figure 1), just like performance, maintainability and reliability. It is actually a part of the general discipline of Survivability which addresses a number of other factors. If it were possible, for instance, to never be detected on the battlefield then vulnerability reduction would not be necessary. We know, however, that is not a realistic approach so that leads us to the need for conducting trade-off studies. By properly addressing these various major disciplines, substantial savings in equipment and personnel can be realized.

Why is it needed? Perhaps if the early Greeks had conducted a vulnerability analysis on the warrior Achilles, (Figure 2), they would have protected his heel. Then he would have survived the battle. In the same sense, if an expensive system has an achilles heel, it can be lost to an indiscriminate bullet from a soldier's rifle. If you were to conduct a study of weapons available on the battlefield, you would always find a large amount of rifleman, and they can be anywhere and they can shoot anytime.

Another aspect of vulnerability reduction analysis, which may not be immediately apparent, is that it forces the designer to identify his critical components. By reviewing his system, the designer can also see the necessity for such things as fail-safe design, which would enable the system to survive in the event of a malfunction due to faulty parts or maintenance. In many cases, whether or not the component fails due to "ballistic damage" or "accident damage", the outcome to the system is the same. (Figure 3) Just to cite one example of this, the (Figure 4) gearbox located at the front of the turbine engines on the CH-47, transfers the power generated by the engines and through the proper selection of shafting and gears drives the rotor systems. The shafts go through a tunnel from the engine nacelle to the combining transmission in the rear pylon. We have documented cases of ballistic damage to this gearbox where lubrication was lost and due to the heat buildup, a fire was started in the gearbox. This fire was then drawn down the tunnel into the pylon resulting in a larger fire in the tail pylon. We were also able to document the same phenomena occurring, when due to malfunction a bearing failed in the gearbox. Similar fires resulted and aircraft were

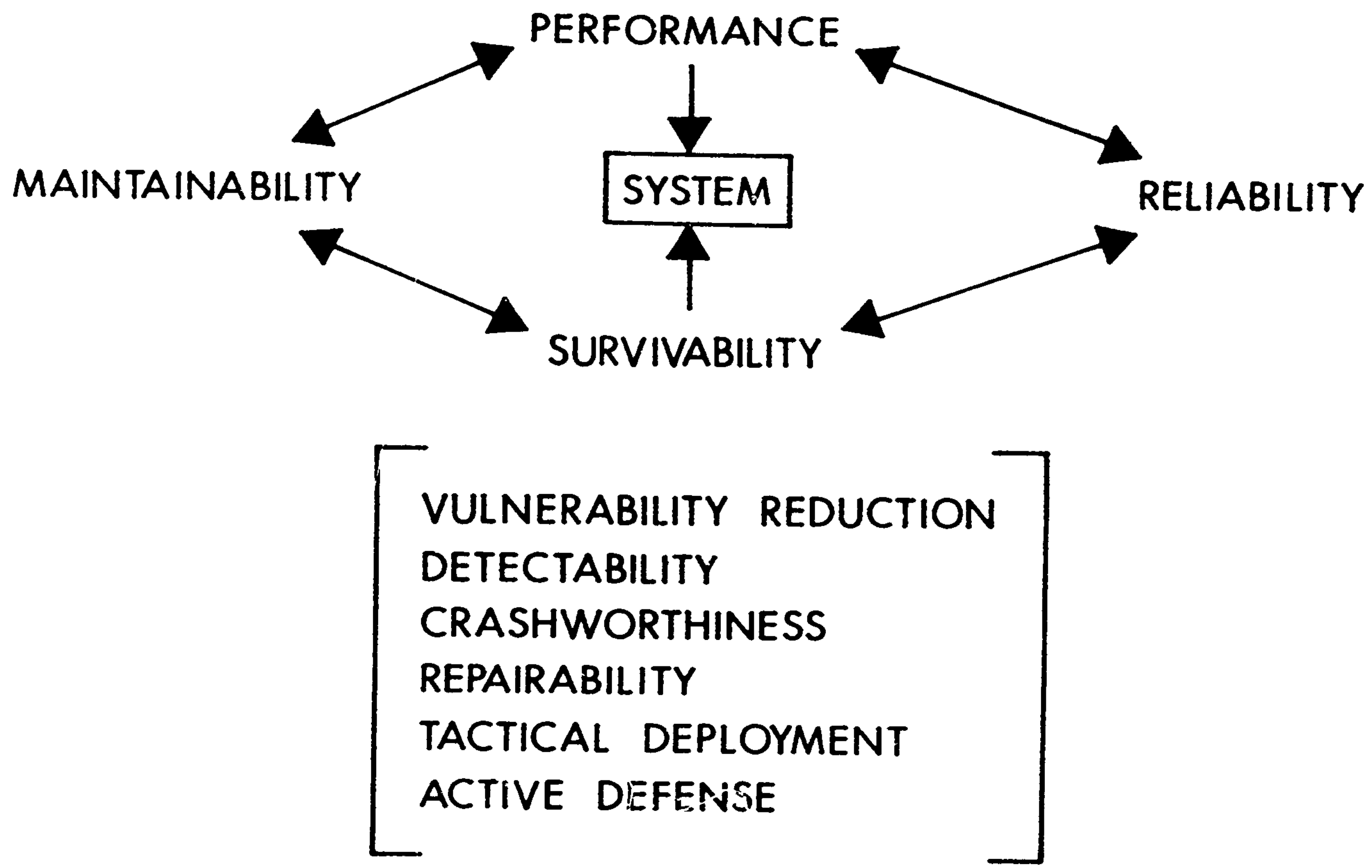


Figure 1 System Study Disciplines

Figure 2 Achilles

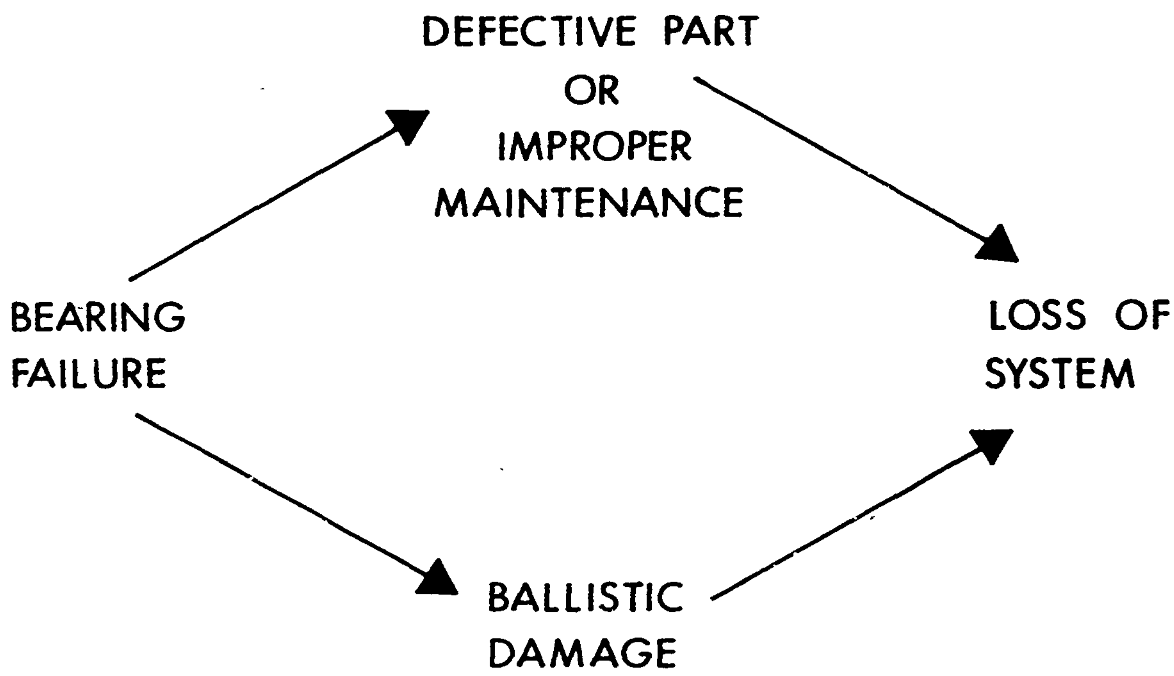


Figure 3 Component Failure Effect

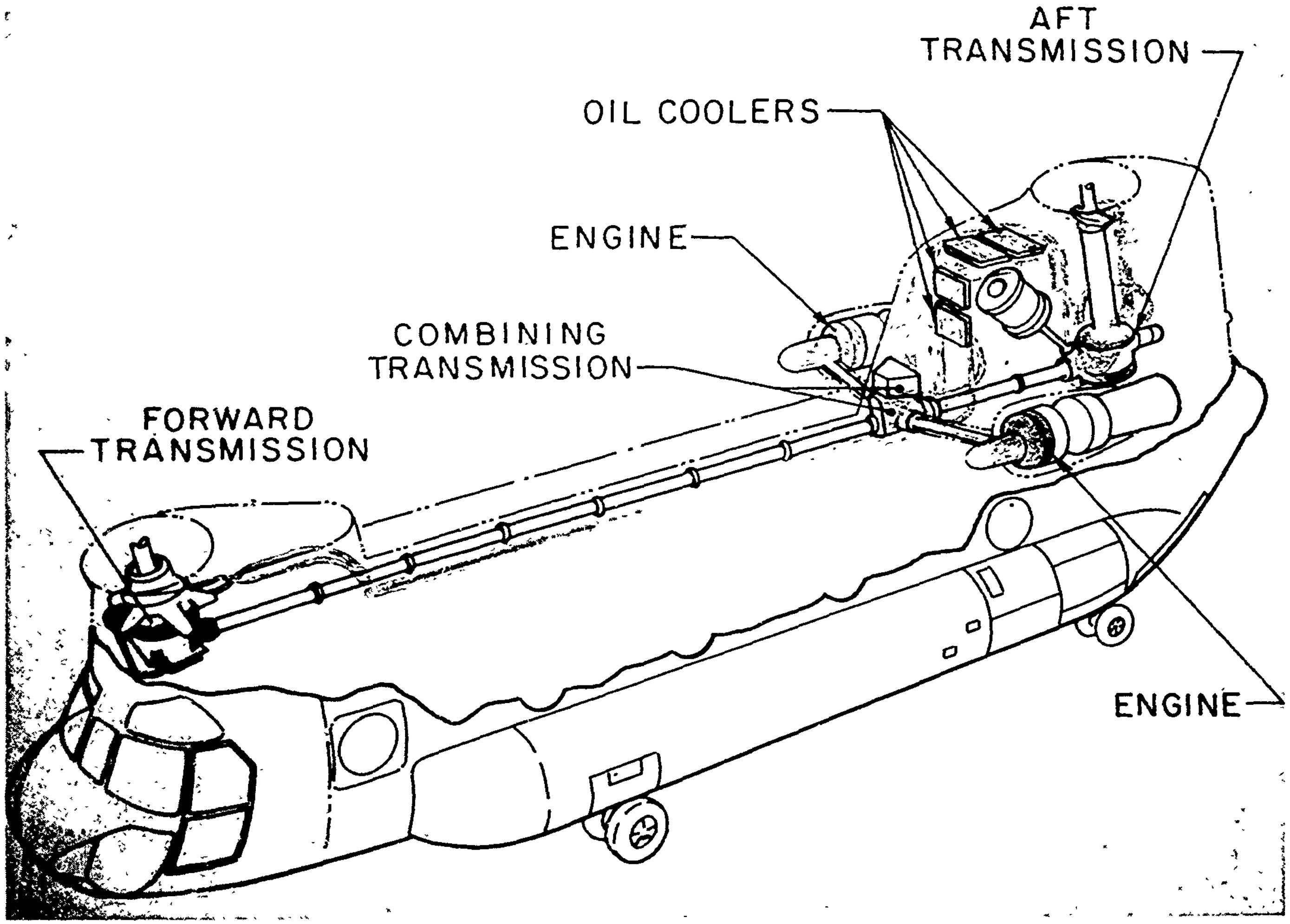


Figure 4 CH-47 Drivetrain

lost. An engineering change has been proposed which will eliminate the possibility of the fire entering the pylon, restricting the fire to the engine nacelle where it can be contained.

Another example (Figure 5) is the comparison of combat and accident data for helicopter transmission systems. In both cases, loss of oil is the primary damage mechanism. While the combat data indicates a more severe environment, the percent of crashes is not too different and the forced landings look alike if some allowances are made for the crew decision to set down or not. What are called mission aborts in combat could be precautionary landings in the accident category.

How do you then determine what is needed? After describing the kill categories, threats and target, the correct methodology will produce a measure of the vulnerability of the system. This will identify the critical components. Other means that are available are combat damage reports and controlled damage laboratory studies. Reliance on only one of these means, however, could be misleading, so it is important to obtain as much information as possible for the analysis.

We have conducted quite a variety of combat damage studies based on experiences in Vietnam. Previous to these studies being conducted we had also made predictions of loss rate for most of the aircraft that were used in that conflict. These predictions were based on our estimates of kill probability ($P_{K/H}$). When we started to compare the combat loss rate with our predicted rate we found good agreement on an overall basis. When we tried to subdivide this into particular components we found that the actual experience and the predicted reaction did not always agree. Upon closer examination we would usually find that what we had predicted as no kill would be producing kills and in a few instances what we had thought might be a problem turned out to be damage tolorent. When we were alerted to the loss of aircraft by damage to components previously thought to be invulnerable we would obtain these components and test them experimentally at our facility. An example of this type of problem can be shown by the combuster can of the T63 turbine engine used in the OH-6 and OH-58 aircraft. Based on previous experience with larger engines, we did not predict any vulnerable area for the combuster can. Combat data showed that this was indeed a problem. We initiated a controlled test study on engines that were made available to us and from this study determined the can area loss that would produce an engine kill. This in turn led us to the development of the relationship shown in Figure 6. As is evident from this figure it does not take much to produce a hole or holes large enough to cause a kill of the T63 engine, but it will require a large caliber threat to produce the hole or holes large enough to produce a kill on an engine like the J65. This does reflect the overall size of the engine and is related to the amount of air that can be bled off the engine without causing a stoppage. For our OH-6 and OH-58 aircraft the immediate fix was a piece of armor. For the future we are investigating the use of different materials for combuster chambers so that bullet impacts would not make large tearing holes in the chamber, but rather only a hole the

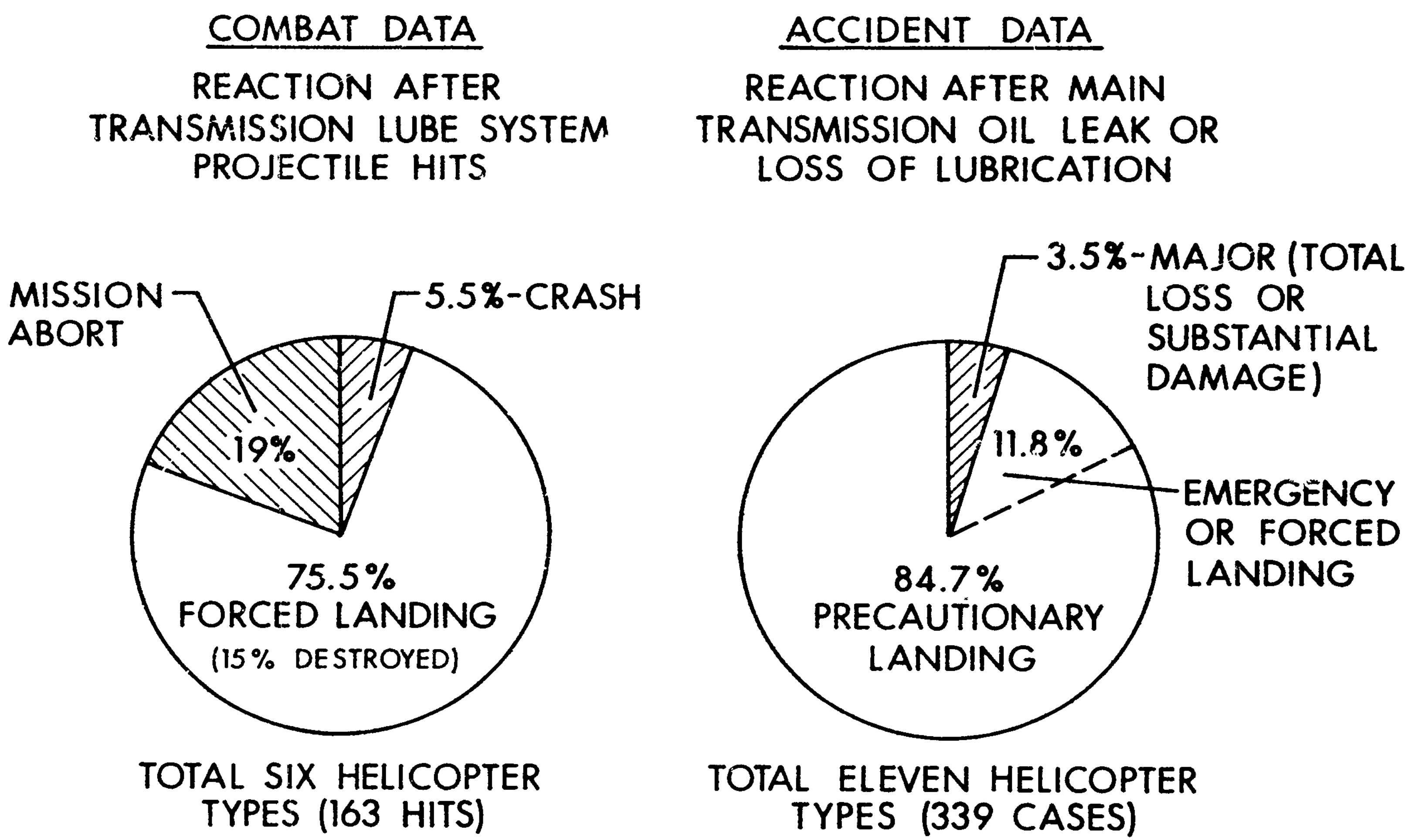


Figure 5 Comparison of Combat and Accident Data for Helicopter Transmission Systems

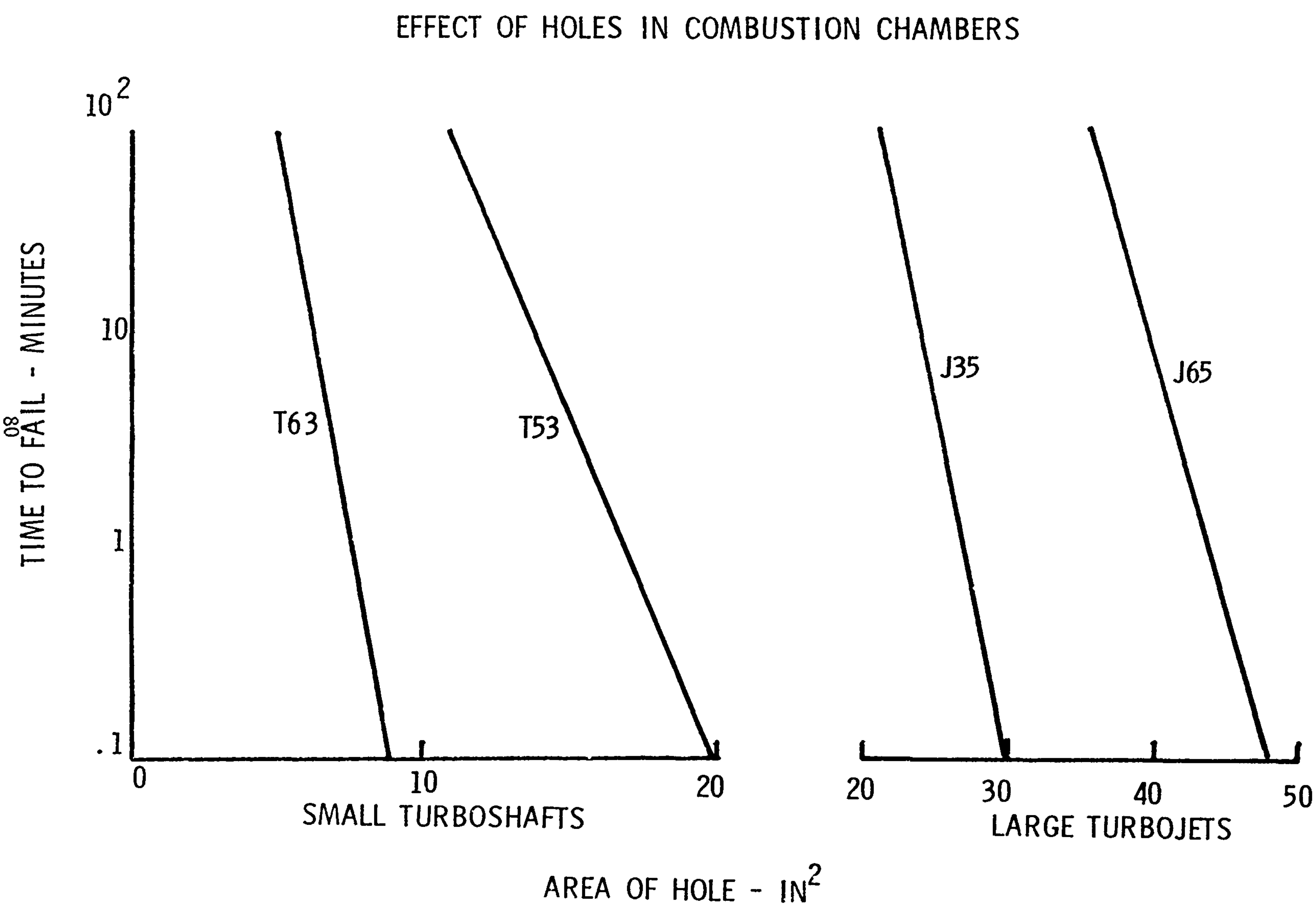


Figure 6 Effect of Holes in Combustion Chambers

size of the bullet. Because of this kind of background of experience we have been able to suggest to designers what the weak points of a component or system might be and in many cases also suggest a way to fix the problem.

A number of years ago, we put together the ABCD's of Vulnerability Reduction (Figure 7). While these are slanted toward aircraft systems, the principles apply to both air and surface systems. If your design is already in hardware stage, in many cases the only alternative is to add armor (Figure 8). There are some obvious penalties though in added weight, more difficult maintenance and degraded performance. For personnel, armor is usually the only alternative as there is not much we can do to reengineer the man. If you are just beginning (Figure 9) to design the system, by judicious placement of components, it is possible to locate critical components so that they are masked by non-critical or less critical components. If I might use another aircraft example (Figure 10), we now try to put engine accessary components on top of the engine so they are masked by the engine itself. For surface targets, one example that comes to mind is the fuel tank of a truck. Relocating this tank to a position just aft of the truck cab, between the main beam structure underneath the cargo floor, significantly reduces the probability of causing a fire from munitions.

Another alternative that is available (Figure 11) is to group a number of small critical components so that the total vulnerable area is smaller. This also allows for more efficient use of armor decreasing the weight penalty. Many systems have built in redundancy for safety or performance reasons (Figure 12). If the redundancy features are separated so that the ballistic threat cannot defeat both paths, then you have achieved vulnerability reduction and enabled the system to survive. Another approach, which should be obvious but many times isn't, is the elimination (Figure 13) of components. A really critical review of the components will show in many cases that what you thought was necessary is, in fact, just nice to have. By making the simplest possible machine, consistent with all requirements, savings are experienced not only in vulnerability but in reliability and maintainability. This principle is also consistent with the Human Factors requirements. Some other techniques which should be mentioned are miniaturization, fire prevention, ballistic tolerance, fail-safe design, crashworthiness and anti-detection. Some of the new technology in composite materials, new fuels, fire resistant hydraulic fluids, new armors and improved propulsion and control systems, used properly, will do much to reduce vulnerability.

When is the best time to apply the principles of vulnerability reduction? Figure 14 will show the relative cost of application during the life cycle of a system. In the beginning, the greatest expenditure is in time. Paper, pencils and erasers are the main items of expenditure. Impact on the system as far as weight is concerned can be minimized. As the system turns into hardware, it becomes more and more difficult to

Figure 7 A,B,C's of Vulnerability Reduction

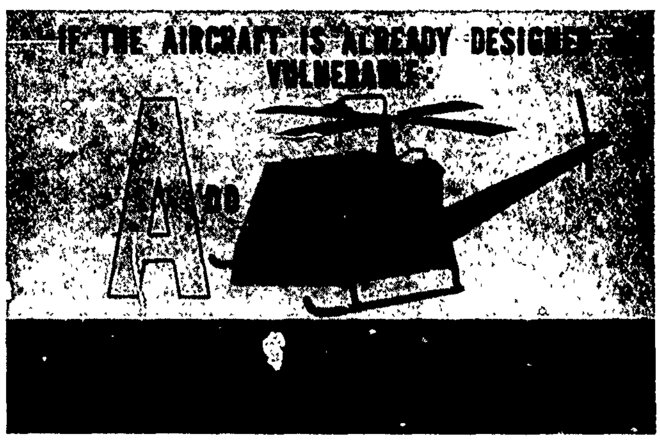


Figure 8 The "A" Principle

Figure 9 The "B" Principle

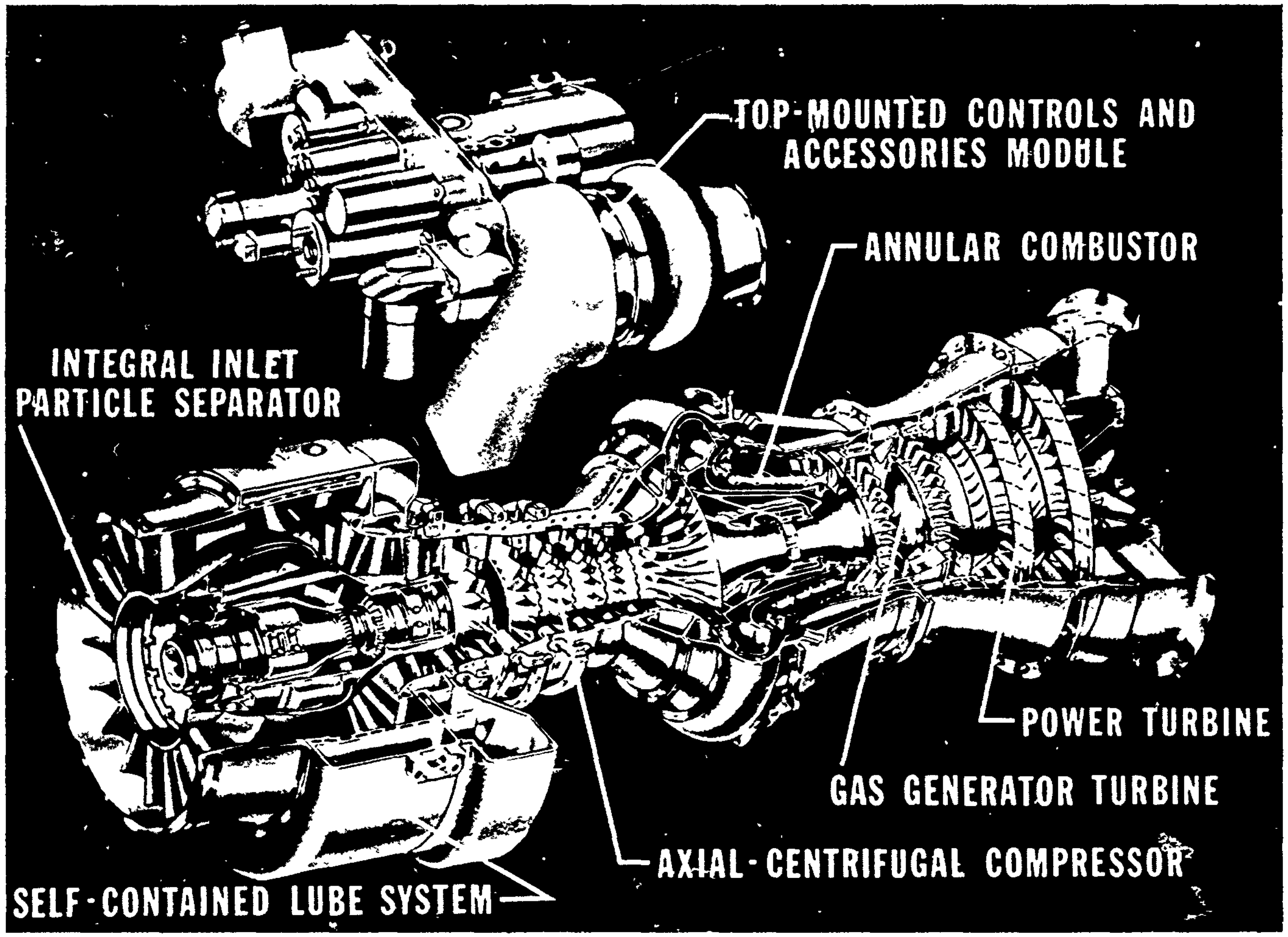


Figure 10 Engine Accessory Module Placement

Figure 11 The "C" Principle

Figure 12 The "Duplicate and Separate" Principles of Vulnerability Reduction

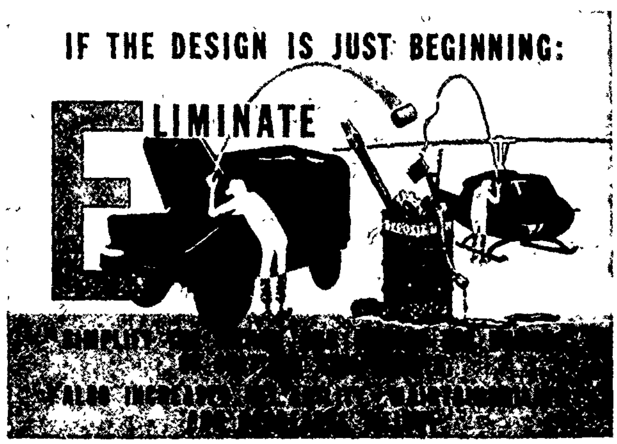


Figure 13 Eliminate Unnecessary Components

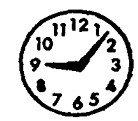
TIME FRAME	RELATIVE COST TO SYSTEM		
	$		
PRELIMINARY DESIGN	LOW	MINIMAL	HIGH
ADVANCED DEVELOPMENT	LOW	MINIMAL	HIGH
PROTOTYPING	MEDIUM	MEDIUM	MEDIUM
ENGINEERING DEVELOPMENT	HIGH	MEDIUM/HIGH	MEDIUM
FIELD SERVICE USE	HIGH	MEDIUM/HIGH	LOW

Figure 14 Vulnerability Reduction Features

make changes. When changes are made this drives the weight and dollar cost factors upward. The time feature lessens because it doesn't take as long to define the problem and many alternatives that could be studied are not practical due to the hardened design of the system.

An example of one system which is applying vulnerability reduction principles from conception to field delivery is the UTTAS. A review of this system will help to illustrate the principles already mentioned.

The fuel subsystem has five features which are being addressed (Figure 15). The items listed are directed to preventing fuel loss from the containers. In this way fire is minimized. The combination of suction fuel feed and feed redundancy prevents fire and assures continuous fuel feed to the engine. While none of these features prevent ballistic damage, they minimize it so that the aircraft can return to base. If we look at the drive subsystem we can rate the need for preventing complete oil loss. This can be accomplished in a number of ways, depending upon the design of the component. We have also developed a rationale for designing driveshafts so that they can function after being hit by various bullets.

For the engines themselves we have determined that these items are of primary importance (Figure 16). If you remember the earlier figure of the T 700 engine you will note that these items were also cited there. Once again it is important to have some kind of a backup lubrication system to assure the aircraft of being able to return to base. When we consider the total aircraft the placement of the engines is important as is the prevention of fire.

The next three subsystems on Figure 17 are not usually critical when the 7.62 threat is considered. The rotor system has not been a significant problem in a low intensity war but in a mid- or high-intensity war they could be significant. At the present time the airframe manufactures are very close to having a rotor blade design that will be able to withstand a small HE projectile impact. This is an indication of what can be done if the requirement is spelled out and the designers take the responsibility seriously. The other subsystem features should be obvious.

As expressed previously the crew is armor dependent but the addition of the crashworthy fuel system provides protection in the event the aircraft does crash (Figure 18). Records indicate that we have experienced no casualties due to fire where the aircraft was equipped with this system. The flight controls have a wide variety of features as you can note.

While these features were detailed for the UTTAS the kinds of designs produced could be applicable for a number of other systems, both aircraft and surface vehicles.

UTTAS VULNERABILITY REDUCTION

SUBSYSTEM	FEATURES
PROPULSION (FUEL SUBSYSTEM)	SUCTION FEED FUEL STORAGE/FEED REDUNDANCY SELF-SEALING TANK/LINES FIRE PREVENTION IN VOIDS MINIMIZE HYDRAULIC RAM EFFECTS
PROPULSION (DRIVE SYSTEM)	FAIL SAFE LUBRICATION DAMAGE TOLERANT DRIVESHAFTS CRITICAL BEARING PROTECTION

Figure 15 UTTAS Vulnerability Reduction

UTTAS VULNERABILITY REDUCTION

SUBSYSTEM	FEATURES
PROPULSION (ENGINES)	INTEGRAL OIL SYSTEM
	EMERGENCY LUBRICATION
	COMPONENT ARRANGEMENT/LOCATION
	SMALL BASIC CONFIGURATION
	OVERTEMP & OVERSPEED PROTECTION
	INLET PARTICLE SEPARATION
PROPULSION (ENGINE INSTALLATION)	REDUNDANCY/SEPARATION
	FIRE PREVENTION/EXTINGUISHING

Figure 16 UTTAS Vulnerability Reduction

UTTAS VULNERABILITY REDUCTION

SUBSYSTEM	FEATURES
ROTORS	DAMAGE TOLERANT STRUCTURE
	FAIL SAFE TAIL ROTOR ASSEMBLY
ELECTRICAL	REDUNDANCE/SEPARATION
	FAIL SAFE
AIRFRAME	DAMAGE REPAIRABILITY
	DAMAGE TOLERANT STRUCTURE

Figure 17 UTTAS Vulnerability Reduction

UTTAS VULNERABILITY REDUCTION

SUBSYSTEM	FEATURES
CREW	SEAT ARMOR
	CRASHWORTHY FUEL SYSTEM
FLIGHT CONTROLS (INCLUDING HYDRAULICS)	REDUNDANCY/SEPARATION
	JAM RESISTANCE/OVERRIDE
	DAMAGE TOLERANT COMPONENTS
	FAIL SAFE HYDRAULICS
	FAIL SAFE ANTI-TORQUE
	SAFE HYDRAULIC FLUID
	SELECTIVE ARMOR

Figure 18 UTTAS Vulnerability Reduction

Now, what did all these do for us. We reduced the vulnerability of the UTTAS to the small arms API threat by 90% from that of the UH-1H which it will replace (Figure 19). We also, by use of the same techniques, reduced the vulnerability to the 23mm HEI threat by 50%. This means that our expected loss rate will be reduced dramatically. While we might spend a little more for replacement of parts we will not be spending a large amount for replacement of the whole aircraft.

Who is it that can do the vulnerability reduction analysis? The bright designer (Figure 20) who is intimately familiar with his system. He is the one who can best determine the criticality of components - who can determine the best placement of components - who can, with the help of the Army vulnerability experts, design and build systems which will give the Army the performance, maintainability, reliability and survivability it needs. Only in this way can we be assured of getting the most for our money and be equipped to field an Army second to none!

UTTAS VULNERABILITY REDUCTION PAYOFF

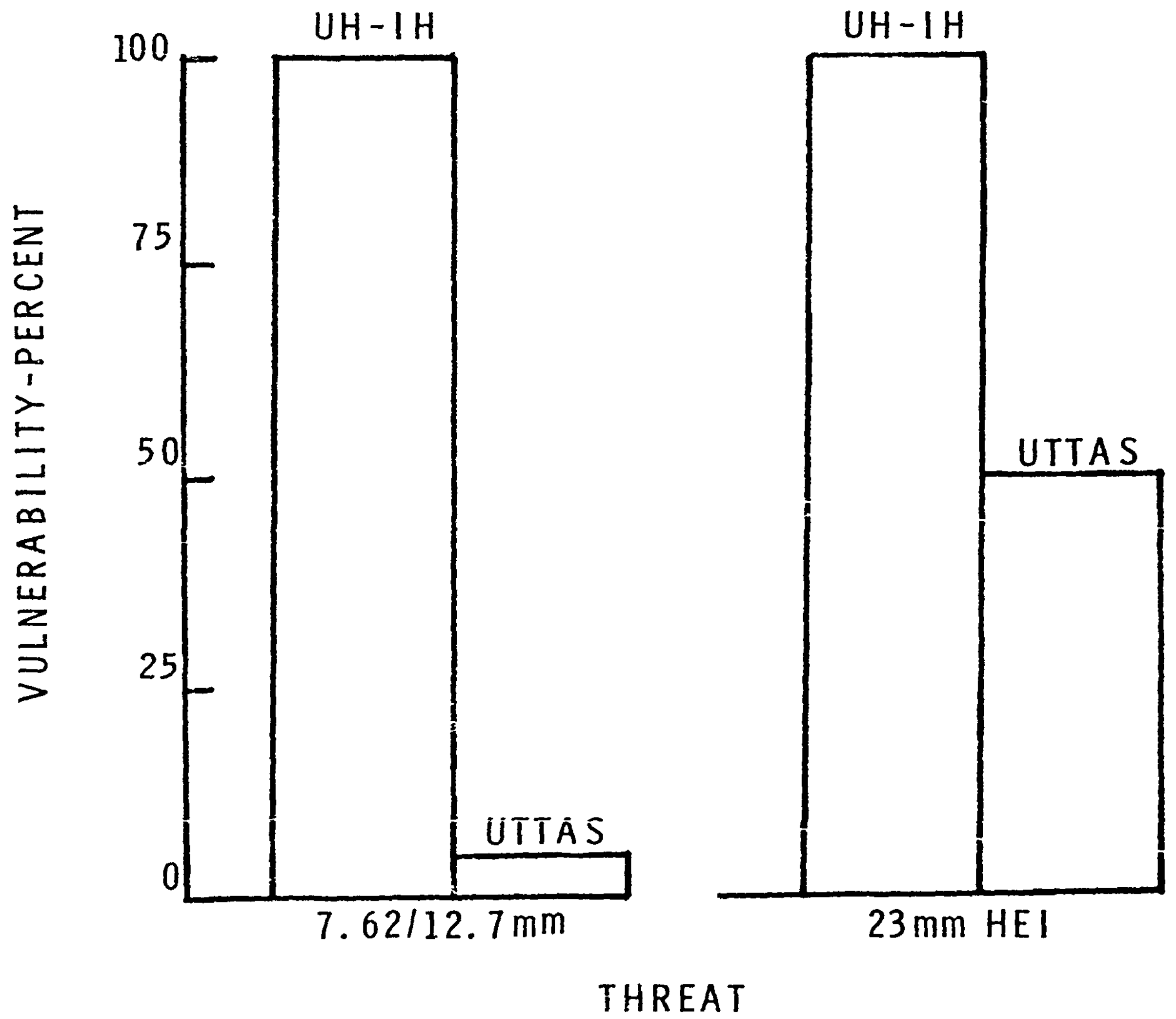


Figure 19 UTTAS Vulnerability Reduction Payoff

Figure 20 The Designer

COMMODITY COMMAND VULNERABILITY ANALYSIS TEAMS

Tamio Shirata

HEADQUARTERS, U.S. ARMY MATERIEL COMMAND
WASHINGTON, D.C.

The topic I'm covering this morning is the AMC Commodity Command Vulnerability Analysis Teams or as we refer to them, VATs. The VATs came into being about 4 years ago. Before discussing why, let me set the stage for the environment which led to the VATs.

My remarks are going to be restricted to vulnerability and vulnerability reduction to non-nuclear ballistic effects, because the nuclear effects area is the responsibility of others in AMC and it has received ample attention over the years, which is not so in the non-nuclear field. Vulnerability and vulnerability reduction activities in the field of non-nuclear kill mechanisms such as fragments, bullets, blast, kinetic energy, shaped charge and others have been pursued by the Army for over 25 years. Although this is a significant amount of time, this activity, until recently, has been limited to consideration primarily in combat vehicles (tanks, APCs and the like), aerial targets (primarily fixed wing aircraft and helicopters), and personnel. The attitude toward the need for vulnerability reduction to achieve greater survivability to non-nuclear effects has been and continues to be mixed. It's like the story of the 85 year old man who wooed and won the hand of a 20 year old girl. On the day of the wedding ceremony, the best man cautioned the old man to take it easy because this type of experience could be fatal. The old man shrugged his shoulder and indicated that he was not concerned, if she dies, she dies.

In 1969, AMC was faced with a problem of how to evaluate and utilize a lot of data that was obtained from the acquisition and testing of our munitions against foreign materiel. Several possibilities were considered, but the two most practicable ones were:

a. Provide the Ballisti Research Laboratories (BRL) with additional manpower spaces and the dollars to conduct the entire Foreign Equipment Vulnerability Analysis program, called the FEVA program, or

b. Involve the Major Subordinate Commands such as MICOM, ECOM, TACOM and others as well as the BRL in the FEVA program without the need for additional personnel spaces.

The decision was made to involve the Major Subordinate Commands and to formulate VATs. We were motivated by several factors.

a. We wanted to get the Commands directly involved with vulnerability reduction measures in the design of their materiel in order to achieve greater battlefield survivability.

b. The approach offered the least impact on additional personnel resources since we felt that the commands could draw upon their existing resources.

c. Funding support would be minimal and limited to support a small core of personnel (3 or 4) at each command. In time we were hopeful that the importance of having a vulnerability reduction capability would be demonstrated and recognized in our commands, that they would put whatever resources they needed, both personnel and dollars, into the continued support of the program.

d. Once trained, it was hoped that the VATs could take some of the vulnerability workload off of the BRL and allow them to put more attention to improving vulnerability techniques, methods and the acquisition of data.

It was in this same time period that our headquarters undertook a thorough study of our vulnerability program because it was felt that the on going program was deficient in many respects; many targets and materials were not being addressed in the program. As a result of this study the program was expanded into a more comprehensive and cohesive one. It was restructured into a single line item project from 4 or 5 different projects. It now includes as Mr. Hoffman has indicated the general areas of ground mobility and firepower targets, logistical and tactical targets, aircraft and missile, wound ballistics, methodology and support technology and the VATs. We pumped more dollars into it although we continue to have problems in maintaining a suitable level of support because of tight budgets.

To emphasize the importance of vulnerability reduction and battlefield survivability an AMC regulation 70-53 has been published which extends the scope of the VATs to vulnerability reduction of AMC materiel, i.e., beyond the analysis of foreign targets. We have been moving toward lead laboratories for selected technology areas and the BRL has been chartered as the Lead Laboratory for Vulnerability Technology.

Getting back to more specifics on the VATs, a program of training was begun the latter part of 1969 using foreign materiel and equipment and conducting various tasks to acquire the necessary vulnerability skills. The commands enthusiasm in support of the program was not overwhelming. I recall that ECOM, for instance, initially participated very reluctantly because they could not see how they needed to be involved with vulnerability measures. As training progressed and the importance of vulnerability reduction to achieve greater battlefield survivability became evident, ECOM changed their opinion 180° and now they are one of our better VATs. Very recently as an outgrowth of the Communications Systems Review in

the Army, DA Staff is placing more emphasis on survivability of communication equipment to non-nuclear effects as well as nuclear effects. Fortunately, we have begun addressing this area, but we have just scratched the surface. There is a lot of work to develop the techniques, the analysis capability, vulnerability data, and the design features which will enable us to respond adequately in the communication field.

By-in-large we are getting the support necessary for viable VATs at the Commands, but I don't mean to imply that we have solved all our problems. Many of the VAT's have developed to a point where they are attacking problems for their own commands and project managers which is very encouraging for those of us who were involved in the genesis of VATs.

In summary the active consideration of vulnerability reduction to both nuclear and non-nuclear effects is a vital part of the design of Army materiel. We look to the VATs to play a significant role in helping to achieve greater battlefield survivability for the materiel we develop and field. The vulnerability and vulnerability reduction efforts are essential for:

a. Weapon and munition designers to assure that they have the best vulnerability information that tells them what kinds of warheads are best to defeat the targets we expect to engage.

b. Our material designers have the basis to design and develop materiel with the best battlefield survivability.

c. Analysts who need vulnerability data inputs to evaluate and select the best materiel options.

You in industry as well as in DOD are encouraged to contact our VATs and the BRL so that proper attention can be given vulnerability measures as well as other factors such as performance, cost and effectiveness, tradeoffs in designing and developing the best materiel for the Army. Thank you.

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